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Pinar Korkmaz

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Abstract

Climate change is recognized as a global consequence due to the global temperature increase in the 21st century. To reduce the impacts of climate change on society, human health, biodiversity, and the future of the environment, the Paris Agreement was ratified in 2015. To cut GHG emissions, the Paris Agreement's commitments require structural changes in the energy system, considering that two-thirds of the total GHG emissions come from the energy system. As a current climate change policy leader, the EU shall maintain its role by achieving GHG reduction targets. Reducing the energy sector emissions within 30 years demands an energy transition that will bring macro-economic and environmental impacts together with the deployment of mitigation technologies. These will play a key role in each sector to achieve the determined reduction targets. The cost of mitigation technologies and their potentials may cause uncertainties to define the transformation pathways. Considering these elements involved in the energy system analysis, this thesis examined the energy transition in the EU by internalizing macro-economic impacts, health damage costs, and uncertainties together with cause-effect relationships between interconnected sectors through a model-based analysis to advance insights to make the transition real. As a first step, the regionalized TIMES PanEU model was employed as a foundation of the integrated assessment framework. It was further developed through links with an impact assessment model, EcoSense, to evaluate the effect of the externalities, with a general equilibrium model, NEWAGE, to assess the influence of the economic variations in the energy system model. A decomposition analysis evaluated the role of the main drivers in the decarbonization of the system. To identify the impacts of externalities considering a high renewable energy target, further scenario analysis was carried out in an additional step. The integrated assessment framework was later applied for a detailed pathway analysis to study the cause-effect relationships between interconnected sectors considering the various reduction targets in the sectors as well as the availability of different technologies. In the last step, to identify the impact of uncertainties on the transport sector's development based on the feedback from the decomposition and pathway analyses, stochastic modeling was applied. The findings showed that an integrated assessment framework that internalizes the externalities and macro-economic variations reduces the energy transition costs. To go beyond the 90% reduction target, technologies such as biomass CCS - which are not commercially available yet - will also be required. Although biomass can be employed in different parts of the energy system, integrating externalities into the energy system analysis, having various reduction targets, and diverse technology options in different but interconnected sectors can change its utilization and role of the energy carrier. The utilization might even alter the hedging of uncertainties with its available potential. To hedge the cost uncertainty with the mitigation technologies based on their learning, early investments will be required, which could change the burden-sharing between interconnected sectors to reduce the GHG emission in the energy system.

Kurzfassung

Der Klimawandel wird als globale Folge des globalen Temperaturanstiegs im 21. Jahrhundert anerkannt. Um die Auswirkungen des Klimawandels auf die Gesellschaft, die menschliche Gesundheit, die biologische Vielfalt und die Zukunft der Umwelt zu verringern, wurde 2015 das Pariser Abkommen ratifiziert. Um die Treibhausgasemissionen zu reduzieren, erfordern die Verpflichtungen des Pariser Abkommens strukturelle Veränderungen im Energiesystem, da zwei Drittel der gesamten Treibhausgasemissionen aus dem Energiesystem stammen. Als derzeitiger Vorreiter in der Klimapolitik wird die EU ihre Rolle beibehalten, indem sie THG-Reduktionsziele erreicht. Die Verringerung der Emissionen des Energiesektors innerhalb von 30 Jahren erfordert eine Energiewende, die makroökonomische und ökologische Auswirkungen mit sich bringt, sowie den Einsatz von Technologien zur Emissionsminderung. Diese werden in jedem Sektor eine Schlüsselrolle spielen, um die festgelegten Reduktionsziele zu erreichen. Die Kosten der Dekarbonisierungstechnologien und ihre Potenziale können zu Unsicherheiten bei der Festlegung der Transformationspfade führen. Unter Berücksichtigung dieser Elemente, die in die Analyse des Energiesystems einfließen, wurde in dieser Arbeit die Energiewende in der EU untersucht, indem die makroökonomischen Auswirkungen, die Kosten für Gesundheitsschäden und die Unsicherheiten zusammen mit den Wechselwirkungen zwischen den miteinander verbundenen Sektoren im Rahmen einer modellbasierten Analyse internalisiert wurden, um Erkenntnisse zu gewinnen, die die Energiewende Wirklichkeit werden lassen. In einem ersten Schritt wurde das regionalisierte TIMES-PanEU-Modell als Grundlage für den integrierten Bewertungsrahmen verwendet. Durch Verknüpfung mit dem Modell EcoSense, konnten die Auswirkungen der externen Effekte bewertet werden, und durch die Verknüpfung mit dem allgemeinen Gleichgewichtsmodell NEWAG wurde der Einfluss wirtschaftlicher Variationen im Energiesystemmodell bewertet. Eine Dekompositionsanalyse zeigte die Rolle der Haupttreiber bei der Dekarbonisierung des Systems. Um die Auswirkungen der externen Effekte unter Berücksichtigung eines ambitionierten Ausbauziels Ziels für erneuerbare Energien zu ermitteln, wurde in einem weiteren Schritt eine Szenarioanalyse durchgeführt. Der integrierte Bewertungsrahmen wurde anschließend für eine detaillierte Pfadanalyse verwendet, um die Ursache-Wirkungs-Beziehungen zwischen miteinander verbundenen Sektoren unter Berücksichtigung der verschiedenen Reduktionsziele in den Sektoren sowie der Verfügbarkeit verschiedener Technologien zu untersuchen. Im letzten Schritt wurde eine stochastische Modellierung durchgeführt, um die Auswirkungen von Unsicherheiten auf die Entwicklung des Verkehrssektors auf der Grundlage der Rückmeldungen aus den Zerlegungs- und Pfadanalysen zu ermitteln. Die Ergebnisse zeigen, dass ein integrierter Bewertungsrahmen, der die externen Effekte und makroökonomischen Schwankungen berücksichtigt, die Kosten der Energiewende reduziert. Um über das 90%-Reduktionsziel hinauszugehen, werden auch Technologien wie Biomasse-CCS benötigt, die noch nicht kommerziell verfügbar sind. Obwohl Biomasse in ver-

schiedenen Teilen des Energiesystems eingesetzt werden kann, können die Einbeziehung externer Effekte in die Energiesystemanalyse, verschiedene Reduktionsziele und diverse Technologieoptionen in verschiedenen, aber miteinander verbundenen Sektoren ihre Nutzung und Rolle als Energieträger verändern. Die Nutzung kann sogar die Absicherung von Ungewissheiten durch das verfügbare Potenzial verändern. Zur Absicherung der Kostenunsicherheiten bei den Dekarbonisierungstechnologien auf der Grundlage von Lerneffekten sind frühzeitige Investitionen erforderlich, was die Lastenverteilung zwischen den miteinander verbundenen Sektoren bei der Reduzierung der Treibhausgasemissionen im Energiesystem verändern könnte.

1 Introduction

1.1 Motivation

According to the European State of the Climate [1], 17 of the 18 warmest years in history were experienced in the 21st century. As a result of the warmest years experienced on the planet, the global average temperature surpassed +1°C in 2016 compared to the average temperature in the 20th century. The actual increase is measured as 1.3 °C [2]. 1°C of this temperature increase has been mainly attributed to human activities [3]. European cities have already experienced the reflection of this change. They are +1°C warmer on average in this century than 20th century [4]. This temperature increase can have severe impacts in the middle term on global human health, biodiversity, weather conditions, and the future of the environment [5]. Therefore, climate change is recognized as a global phenomenon that threatens humanity's security and prosperity on the entire planet.

To tackle climate change and its impacts globally, the Paris Agreement was signed by 197 countries in 2015 [6]. The agreement aims to keep the global temperature increase below 2°C above pre-industrial levels and make an effort to keep the rise below 1.5°C. According to the Paris Agreement [6], all parties shall disclose their middle and long-term strategies to reduce greenhouse gas (GHG) emissions to help societies prepare for the actions. At least two-thirds of the total GHG emissions produced globally are caused by the energy system [7]. The energy system's contribution to GHG emissions is even higher in the EU, totaling 75% [8]. Therefore, the Paris Agreement's commitment requires structural changes in the energy system, the so-called energy transition [9]. Delayed actions will increase the cost of the energy transition together with the hindered technological developments. The importance of early action is also stated by Ursula von der Leyen, the European Commission President, in one of the European Parliament's meetings: "We do not have a moment to waste any more on fighting climate change. The faster Europe moves, the greater the advantage will be for our citizens, our competitiveness, and our prosperity." [10]. To accelerate the EU's actions on climate change after her statement, the Green Deal was published by the European Commission [11].

According to the Green Deal [11], transforming an industrial sector into a carbon-neutral processes takes 25 years. Therefore, to realize the energy transition, decisions cannot be postponed anymore. Different energy transition scenarios to reduce emissions by 80-95% according to 1990 levels by 2050 with milestones in 2030 and 2040 are discussed in [3]. With the ratification of the Green Deal, net-zero emissions to be achieved by 2050 are also discussed. To continue to be a leader in climate change policy, the EU cannot delay the required actions to limit the global temperature increase any more [3]. To tackle climate change as a union, the EU has already taken definite steps by launching the Energy Union in 2015 toward a sustainable European energy system [3]. Closer cooperation between the Member States is also required to make the transition possible [12]. To contend with climate change, energy transition in the EU is necessary. A long-term strategy for at least 30 years is required to define the different transition pathways [12]. Various aspects such as economy, environment, society, and technological developments are affected by the energy transition or affect the energy transition.

One aspect that needs to be considered within the energy transition is the environmental impacts since burning fossil fuels is the main contributor to higher greenhouse gas emissions and plays a significant role in increasing air pollution in the energy system [13]. Therefore, they can be considered as interrelated problems [14]. Air pollution has significant impacts on human health, costing to the system "health damages". It causes more than 400.000 premature deaths each year in the EU [4]. Decreasing air pollution and its impacts on the environment and human health is also part of the UN sustainable development goals [15]. As they are interrelated problems, climate change mitigations are expected to decrease air pollution impacts as well [16].

On the other hand, the use of biomass in the energy system is expected to increase through the energy transition, as it is deemed to be carbon neutral. However, it is also known that burning biomass creates air pollution, which can also bring severe impacts on health and the environment. Therefore, the expected increase of biomass in the energy system raises questions regarding trade-offs with air pollution impacts [3]. To address the direct trade-off between pollutants and GHG mitigation strategies and to consider the potential increase of pollutants from increased biomass usage, the costs caused by the air pollution on human health can also be internalized in the energy systems [17]. According to the analyses carried out in [13], air pollution co-benefits might have immediate and vital effects such as lower mortality rates on human health. Additionally, in [14], the study shows that global health benefits can be higher than mitigation costs to achieve a decarbonization target. Furthermore, achieving 2°C will bring additional benefits globally considering society's reduced health and climate damages.

Another critical aspect that is essential to be addressed is the economic impacts of the transition and their effects on the energy system. The availability and cost of accessing energy affect Europe’s economic growth and competitiveness compared to other global markets. As determining the climate change strategy for the middle and long term is also critical to estimate the economic growth, the energy transition in the EU will directly impact the economic dimensions of all sectors [3]. The energy transition in the EU will need significant adjustments in all production and consumption patterns, making the process capital intensive [18]. According to [19], changing the energy market system translates to altering how the economy works since structural changes in the energy system, such as moving from fossil fuels to renewables, also require structural changes in the economy. This results in a decoupling of emissions from economic growth.

Additionally, the EU energy transition will also cause changes for the EU 28 trade balance. The increasing demand for domestic and domestically produced energy carriers such as electricity will increase their shares and replace the imported fossil fuels. These adjustments shall directly impact the energy system as well as the economy [18].

Deployment of mitigation technologies may increase energy costs which can lead to a crowding-out effect in the economy. This effect may also harm gross domestic product (GDP) development [18]. GDP and sectoral growth are some of the main drivers in the energy system to determine end-user demand projections [20]. Their impacts have already been discussed in other studies. According to [3], slightly adverse effects on GDP development and sectoral growth are seen at the global and EU level due to energy transition. In [21, 22], it is shown that higher GHG emission reductions in the energy system and the economy, compared to a reference scenario without ambitious reductions, results in a lower gross GDP.

According to [3, 23], there is a proxy between economic growth and a total emissions development path, and this proxy should be considered during the energy transition. The industrial sector can be given as an example here. The industry sector itself is crucial not only in the energy system with high energy demand but also for economic activities. It accounts for a high GDP share in the EU, incredibly energy-intensive industries such as cement, iron and steel, chemicals, and ammonia. However, this means that a high amount of energy is required during production, which produces a high level of greenhouse gas emissions. This proxy shows us the direct relationship between economic growth and energy transition. Therefore, some industry sectors, mainly fossil fuel-based, struggle under strong climate policies [4]. There is also positive feedback between energy system developments and the economy, bringing constructive effects to the energy system. With the Sustainable Europe Investment Plan, the European Commission also aims to increase the investors' interest in sustainable options [24]. As the energy transition is expected to reduce the share of natural gas and oil in the energy mix, the import dependency may also decrease.

Additional to the environmental and economic aspects of the energy transition, the role of mitigation technologies, their deployments, potentials, and uncertainties shall also be part of the analysis as also outlined in the Strategy Energy Technology Plan [25]. Different mitigation technologies have already been developed and become commercially available in the market. Solar PV, hydro, onshore, and offshore wind technologies can be named frontrunners considering the current cost and efficient development of these technologies [3]. As such, they are also expected to facilitate the energy transition [12]. Furthermore, these technologies can already compete in the market with conventional generation technologies considering their levelized cost of electricity [4, 7]. These developments have resulted in the renewable energy share of power generation recently increasing in the EU. Between 2004-2016, RE experienced a steady growth of 6% annually on average [3]. This deployment has also led to further cost reductions for the leading market players and broader system integration requirements [26].

Biomass demand in each sector has increased since 2009 [3]. The increase is expected to be even higher in industry, transport, and electricity with the availability of BECCS. Although biomass is counted as a sustainable energy source, biomass harvesting should not exceed the maximum available potential since it can jeopardize the resource's sustainability. Therefore, uncertainty regarding the availability of the resource in different sectors requires attention during the energy transition. In the transport sector, mitigation technologies have been deployed with electric vehicles and biofuel usage. Bioenergy, renewable fuels, and batteries for e-mobility are the focus for sustainable transport, according to [7]. Although the speed has not been high enough, EVs have already built their technology learning curves, and certain cost reductions are experienced [27]. While biofuels are not widely applied yet in aviation and navigation, according to [28], these transport modes can also be decarbonized starting from 2025 with biofuels' utilization.

Concentrating solar power/solar thermal electricity, offshore wind energy, ocean energy, and geothermal energy are the main mitigation technologies in the electricity sector, according to [7]. Therefore, breakthrough cost reduction scenarios with renewable technologies are still required to accelerate the transition together with new technologies, sustainable solutions, and disruptive innovations [7, 11, 29]. Learning curves are developed and applied in the literature to project future cost reduction of most of the mitigation technologies. Technologies such as solar PV and wind have already benefited from early deployments to reduce investment costs following the learning curve principle [26, 30]. Uncertainty is also an essential factor for cost projections, as different learning curves are already available in the literature with varying learning rates, resulting in different deployment expectations [31, 32, 33, 34]. Additional to the electricity sector, different mitigation technologies have also been developed in other parts of the energy system. Solid biomass, solar thermal, district heating, and heat pumps are examples in the residential sector. Learning curves have also been built for the energy demand technologies in the literature [35]. These technologies can replace the role of gas and oil boilers to meet the heating and cooling demand.

Though they are not classified as renewable energy technologies, nuclear energy and carbon capture and storage technologies are defined as two of the four main routes to a sustainable energy system in [36]. Increase safety for nuclear energy usage is also essential, especially for the Member States that aim to apply this technology for the transition [3, 7]. Carbon capture and storage are also considered potential mitigation technologies with fossil fuels and biomass to store the emissions. Accordingly, biomass CCS can be deployed to produce negative emissions during the energy transition [37]. Different scenario analyses address that negative emissions might be required to achieve a higher than a 90% reduction in the energy system in [3]. Especially for the industry sectors such as cement, aluminum which are not easy to decarbonize the process emissions, negative emissions might be essential during the energy transition.

The energy transition in the EU is required not only to reduce the greenhouse gas emissions but also for the EU to continue its role as a leader in climate change policy with the necessary technological developments and alterations in the society, environment, and economy. Therefore, a systematic methodology is fundamental to assess this energy transition in the EU to make the relevant decisions whenever and wherever it is required and possible. Energy system analysis as a systematic methodology shall be applied with the relevant tools for such an assessment [38]. Energy system models are the tools developed and applied to assess the energy system analysis [38]. However, as discussed, these tools need further improvements to consider the aspects - economy, environment, and technology developments with the relevant uncertainties - which are interrelated problems with the energy transition. The further improvements to consider these aspects are expected to provide better insights for the energy-related issues during the transition, since these aspects either affect the energy transition or are affected by the transition.

1.2 Objectives

The energy transition in the EU is inevitable to achieve the targets committed to in the Paris Agreement. The energy transition should be assessed with a systematic methodology that can be delivered with a model-based analysis covering the entire energy system and all the Member States in the EU as explained in Section 1.1. This analysis shall consider the interactions with air pollution control to integrate the environmental perspective to the transition and macro-economic variations to incorporate feedback from the economy reasoned by the energy transition to the energy system. This enhancement is required to understand the implications and requirements better since these aspects are considered interrelated problems with the energy transition, as elaborated in Section 1.1. Therefore, an integrated and comprehensive approach is required to design the energy system to achieve the required decarbonization targets in the EU. Furthermore, mitigation options need to be identified and verified in various parts of the energy system, considering their uncertainties with feedback loops from the economy and environment during the energy transitions since technology has another essential role during the energy transition, as discussed in Section 1.1.

Considering the requirement of the further analysis to provide better insights for the energy-related issues by integrating the aspects - environment, economy, technology, and relevant uncertainties - this thesis aims to bring the critical but missing additional knowledge for the energy transition in the EU. This objective will be achieved by integrating the macro-economic and environmental impacts to the analysis and identifying the mitigation technologies considering the sectoral interactions and uncertainties to verify their relevance through the energy transition with an integrated assessment approach. Based on this objective, this thesis targets to answer two main research questions:

- **Research Question I:** What are the implications of the trade-offs between the energy system transition and environment and economy along the whole transition pathway in the EU?
- **Research Question II:** What are the key technologies’ roles considering the feedback loops from the economy and environment by taking into account the cause-effect relationships between the interconnected sectors in the energy system and the relevant uncertainties through the energy transition in the EU?

In the following section, Section 1.3, the State of the Art will be reviewed systematically based on these two research questions. After the discussions of the existing methodologies and identification of the existing gaps in Section 1.3., in Section 1.4 the research questions will be revisited to point out the specific contributions of this thesis to the relevant scientific advancement.

1.3 State of the Art

As stated in Section 1.2, this thesis has two main objectives. These objectives are defined based on the need to integrate the environmental, macro-economic, technological aspects with their uncertainties to the energy system analysis by applying energy system models to further the understanding for the energy system transition in the EU as described detailed in Section 1.1.

Although the integrated view is still a need to assess the European energy transition, the studies are available with various approaches to integrate the economic as well as environmental aspects into the energy system analysis separately. Additionally, different scenario analyses are also carried out with several energy system models to identify the strategic technologies' role and implications of their deployments considering several GHG reduction policies.

In this section, the current state of the art is presented. As there are two main research questions defined based on the objective described in Section 1.2, the existing literature is reviewed based on these objectives. Therefore, the section is divided into two sub-chapters to examine the existing work accordingly. In Section 1.3.1, the approaches to integrate the environmental and macro-economic feedbacks into the energy system are elaborated and a discussion is included to summarize the contemporary research with the pros and cons of the existing methods and identify the gaps to advance the knowledge by integrating the environmental and macro-economic aspects. In the following section, Section 1.3.2, the current studies around the scenario and uncertainty analyses to identify and verify the role of the key technologies are described and the section is concluded with a summary to outline the existing gaps for further assessment.

1.3.1 Integration of Environmental and Macro-economic Feedbacks into the Energy System

As stated in Section 1.2., one of the main objectives of this thesis is to assess the trade-offs between the energy system transition and environment and economy along the whole transition pathway in the EU. Therefore, in this section the approaches are defined to integrate the environmental and macro-economic aspects into the energy system analysis, and it is followed with a discussion to summarize the scientific relationship to the first research objective and key identified gaps included in this thesis. Since these aspects are either affected by the energy transition or affect the energy transition, there are feedbacks in between which will potentially provide additional knowledge to the existing European energy system transition insights.

The integrated assessment approach is one of the methods to incorporate the aspects outside of the energy system such as economy and environment into the energy system analysis. Integrated assessment models (IAMs) have been developed and applied in energy system studies to bring diverse perspectives together. Knowledge and understanding from various fields have been aggregated with the help of these integrated assessment models or frameworks. The impact of climate change, its key challenges, and various mitigation strategies can be addressed thanks to these tools. Integrated assessment models have also been performed in the Intergovernmental Panel for Climate Change (IPCC) reports analyzing the possible interactions between economic and social developments and technical systems to decarbonize the system at the lowest cost by identifying its implications for individual countries [39]. There are 6 integrated assessment models developed within the scope of the IPCC reports. The IMAGE model framework, which the PBL Netherlands Environmental Assessment Agency hosts, brings together the models such as macro-economic model MAGNET, a climate policy model FAIR, a biodiversity model GLOBIO, flood risks model GLOFRIS and a human development model GISMO. The IMAGE model analyzes the impacts of decarbonization scenarios on biodiversity loss and human development [40]. MESSAGE-GLOBIOM model framework, hosted by the International Institute for Applied System Analysis in Austria, consists of four different models. These four models are soft linked to each other to run iteratively. It covers the scope of the energy system model (MESSAGE), the land-use model (GLOBIOM), the air pollution and GHG model (GAINS), the macro-economic model (MACRO), and the simple climate model (MAGICC). In the structure, MESSAGE and MACRO run iteratively to optimize the energy system and services costs computed by MESSAGE. Only six commercial end-use demand categories are iterated according to the input from MACRO during the iterations. GLOBIOM model computes the land-use outcomes according to converged results of the MESSAGE-MACRO framework. GAINS model calculates exogenously air pollution emissions, concentrations, and the related health impacts based on MESSAGE-GLOBIOM scenarios [41].

Another IAM framework that belongs to the IPCC family is AIM/CGE, hosted by the National Institute for Environmental Studies in Japan. The framework's foundation is based on the computable general equilibrium model to maximize the welfare in the economy considering the global and country CO_2 emissions, mitigation costs, or carbon taxes [42]. GCAM, a globally integrated assessment model hosted by the Pacific Northwest National Laboratory in the USA, links economic, energy, land-use, water, and earth systems within the framework globally [43]. Global energy, economy, and climate aspects are linked to each other in another IAM, REMIND-MAgPIE as well. The Postdam Institute in Germany hosts this IAM. According to the framework, the macro-economic and the energy system models are hard-linked and further engaged with MAgPIE to consider land-use and agricultural emissions, bioenergy supply, and other land-based mitigation options [44]. The last model framework in the IPCC reports is WITCH-GLOBIOM IAM which Fondazione Eni Enrico Mattei hosts in Italy. WITCH includes a dynamic global model, and it is hard linked with a compact representation of the energy sector. Land use mitigation options are available with a soft link with GLOBIOM, and the future climate characteristics are considered with MAGICC.

Integration of air pollution control has also been discussed with diverse approaches additional to the integrated assessment approach. Two main methods so far applied in the energy system models to integrate the air pollution control in the energy system analyses. The first methodology known in the literature is implementing the damage costs, borne on human health due to pollutants, into the energy system. These cost figures can be calculated either exogenously or endogenously for system optimization. In [45], a methodology was discussed with this approach to integrate the external costs in a TIMES model. The link incorporated the health damages costs caused by the pollutants and damage costs calculated exogenously into the energy system model. The interaction between health damage costs and decarbonization scenarios at a regional level was assessed in [46]. The second method is introduced in [47, 48, 49]. This method suggests implementing the upper emission bounds to control the air pollution in the energy systems. With this approach, without considering the cost, they discussed the alterations in the energy systems to reduce the emissions. The costs borne due to the health damages were not considered in the optimization function.

Additional to the IPCC IAMs, an energy system model and a macroeconomic model has been linked in other studies. The soft-linking approach was introduced without any details for the sectoral level link in [50]. A Swedish energy system model was soft linked to a CGE model in [51]. In the study, a methodology was proposed to integrate the macroeconomic impacts on the energy service demands directly. However, they did not match the residential heating demand with any economic parameter, which is the highest contributor to GHG emissions between the residential energy service demands in an energy system. Their results showed a considerable decline in industrial energy demand after the link, reducing the CO_2 mitigation costs. The CGE models in [50, 51] are not focused on the electricity sector similar to the CGE models which have been part of the IPCC IAMs. The developments in this sector and the role of technologies during the European energy transition are quite crucial as discussed detailed in Section 1.1.

Macro-economic impacts on the energy service demands have been integrated into the energy systems with other methods as well. One of the well-known approaches is to incorporate the price elasticity for the energy service demands into the energy system models. Price elasticity of energy service demand measures the responsiveness of demand after a change of a price for the demand. Investment in low carbon technologies to achieve the GHG reduction policies increases the prices for the energy service demands. Defining the price elasticity endogenously in the model gives the demand response to increase prices [52]. The first implementation of the price elasticity in MARKAL models was carried out in [53]. In [52], the price elasticity was incorporated into the ESME model for the UK. According to their results, demand response can play a critical role during the energy system's decarbonization. The transport sector reacts the most; however, the uncertainty ranges of the price elasticities for the energy service demand is quite big, which also needs to be assessed. In [54], the TIAM-UCL model was further developed by integrating the energy service demands' price elasticity. Their findings showed that the energy-service demand reduction could contribute to the global emission reduction, around 5%. At the sectoral level, the impact can be even higher, 16% at the global level. However, the price elasticity is not dynamic through the time horizon. According to different regions, and the uncertainty range again appears as a challenge with the approach.

Another way of including the macro-economic impacts on the energy service model is to establish a link with the single-sector general equilibrium model MACRO [55]. The Macro model is available as a function similar to the price elasticity in the energy system model generators such as TIMES, MARKAL, MESSAGE. MARKAL-MACRO model was applied to assess renewables' contribution to decreasing the CO_2 emissions in Italy [56]. Required investments for renewable energy technologies created reverse effects on the GDP growth, according to their findings. Similar analyses were also carried out for different regions in different studies with the same model structure [57, 58]. In [59], the MESSAGE-MACRO model was chosen to be performed for the scenario analyses. GDP, energy supply and demand, and energy prices were compared after establishing the different scenarios' link. MESSAGE-MACRO framework has also been applied in different studies to consider the economic impacts in the energy system analysis [60, 61, 62].

Scientific relationship to research objective 1

Integration of macro-economic feedbacks

Three main approaches are discussed to integrate the economic variations for the development of the energy service demand development into the energy system analysis in the literature:

- Implementation of price elasticity: A high range of uncertainty with the price elasticity appears as a drawback for the approach, and the price elasticity values are constant over time. Therefore, the approach does not provide enough flexibility. The data is based on the literature which is not dynamic enough to respond to the changes in the economy due to the transition in the energy system
- MACRO link in the energy system models: This link in the energy system models represents only a single sector general equilibrium model. Therefore, it is mainly GDP that reacts to the changes in the energy system. There is no direct match to integrate the economic feedbacks for all the energy service demands in the energy system models.
- Coupling with a macro-economic model: This approach brings a dynamic solution for implementing the feedback into the energy system models, unlike the other two methods as discussed. Moreover, this approach covers more than one

single sector in the economy. There are also two main applications of this approach in the available: hard-linking with a macro-economic model and soft-linking with a macro-economic model.

- Hard Linking: In the IPPC models, the links are mainly established as hard links. Hard linking refers to automated data processing and exchange, and the models are solved as a whole [63]. Generally, one model dominates the results, and the other model does not have the control over structure [50]. Therefore, it might take flexibility from each model and can limit the decisions mutually. Moreover, transparency can be limited for the data exchange [64].
- Soft linking: This approach brings the advantages of practicality, learning, flexibility, and transparency as the opposite of the hard linking between them. Each model can preserve its strong points [65]. It also provides essential transparency since the data is always accessible during the coupling. The results can also be assessed from the models during the iteration process. The input parameters can be adjusted, if necessary, to make the results of the model consistent for convergence [49]. The link can be altered to increase or decrease the impact from one model to another.

Based on this review, the soft linking with a macro-economic general equilibrium model shines out as the best approach to integrate the macroeconomic variations on the development of the energy service demands into the energy system analysis. As discussed, similar applications are seen in different studies, such as the MESSAGE-GLOBIOM model [41]. However, in this structure, the data exchange link has been limited only to particular commercial end-user demands, and there is no direct match for each end-user demand. In a similar study [51], the link was established for the energy system in Sweden for a similar purpose; however, it was assumed that the economic variations are the only elements that affect the energy service demand developments in this study. Additionally, again there was a limited match between the models. Different impact levels from the economy, i.e., decoupling from the economy on the energy system, have not been discussed. Furthermore, the effect of having different impact levels on the iteration process between the energy system and macro-economic models has not been recognized yet in contemporary research. Not all the energy service demands received feedback from the macro-economic modes, such as residential heating demand, which is the highest contributor to GHG emissions between the residential energy service demands. Besides, any study has not been identified yet which integrates the macro-economic variations air pollution control simultaneously in the energy system during the decarbonization.

Integration of environmental feedbacks

Two main methods have been developed for air pollution control in the existing literature as discussed:

- Setting an emission cap for the emissions from pollutants: This approach does not consider any cost factor around the externalities and only optimizes the emission level. This might also mislead the decarbonization cost for the system.
- Introducing the damage costs in the energy system and optimizing the system cost considering those costs: This approach brings the system cost-optimal air pollution control. The studies [45, 46] did apply this approach to internalize the environmental impacts in the energy system analysis as discussed. However, these studies are limited in terms of their regional scope and do not consider the additional feedback from the economy in the analysis.

Based on this review, the introduction of the damage costs in the energy system analysis comes forward as a better approach since the cost-optimal air pollution is in the interest of this thesis considering the feedbacks between the social cost and energy system.

Key identified gaps included in this thesis in relation to research objective 1

Various applications are available to integrate environmental and macro-economic variations into the energy system since there is feedback between the energy system and those aspects, which shall be considered as interrelated problems, as discussed in Section 1.1. However, an application that considers both of these aspects - environment and economy - together through a soft-link approach with the required flexibility and dynamism to the process for the decisions without high uncertainty, to provide the economic feedback to all the energy service demands in an energy system model, including residential and cost-optimal air pollution control for the whole regions in the EU does not exist yet. In this framework, the impacts of the factors such as social welfare and population must be considered for the demand development along with the macro-economic feedback as discussed in Section 1.1.

1.3.2 Scenario and Uncertainty Analysis for Identification and Verification of the Key technologies

As stated in Section 1.2., one of the main objectives of this thesis is to identify the role of mitigation options and verify them by considering the uncertainties. Therefore, contemporary research is reviewed by focusing on the relevant scenario analyses. The application of energy system models to analyze diverse technologies' roles in different sectors is available with various scenario analyses in the existing literature. The available studies have analyzed different reduction targets to reduce GHG emissions in the energy system to provide relevant insights for the energy transition to address the mitigation technologies' role as well as role of the uncertainties in the energy system analysis and the section is followed by with a discussion to identify the key gaps in contemporary research.

80% GHG reduction target in the EU28 was analyzed in [66] the PRIMES model to focus on the impacts of technology developments on various transformation pathways. The role of different decarbonization technologies such as CCS and EVs was assessed. It was concluded that both technologies would have their roles during the energy transition in the EU28. A similar analysis was also performed within the framework of a project called CECILIA (Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe’s 2050 climate targets) [67]. Their results confirmed the findings in [66] with the role of CCS to achieve 80% GHG reduction in the EU28. Another study [68] was conducted with the European TIMES model, ETM-UCL, to analyze 80% GHG reduction again, focusing on the power sector, particularly for the role of biomass with carbon capture and storage (BECCS). According to their results, the utilization of BECCS reduced the mitigation cost of CO_2 and provided rigidity to other sectors.

85% GHG reduction target analysis was carried out in [69]. The power sector was the main focus of the study again, and the findings were also specific to this sector with the role of mitigation technologies. Different renewable potentials such as low biomass, the impact of restricted nuclear deployment, the availability of CCS according to different timelines, low energy consumption in the energy system were studied with diverse scenario structures. Their results showed that nuclear and solar PV would be crucial technologies during the transition. Conventional CCS, hydro, wind onshore, wind offshore, bioenergy, marine, and geothermal will track these technologies in terms of relevance. As the focus was also rather on the power sector, the impact of the transition in the other sectors was not analyzed within the study's scope.

A recent study published by European Commission has several analyses with the combination of different mitigation options to achieve the GHG reduction targets from 80% to net-zero emissions in 2050 [3]. According to the scenario structures built within the analysis, electrification became the driver, but hydrogen played an important role in transport, industry, and buildings. E-fuel options were also assessed in various parts of the energy system. In the higher reduction target scenarios, beyond 90%, all the mitigation options, including BECCS and other carbon storage technologies, were allowed for a deployment.

Designing 30 years energy transition strategy to reduce GHG in the EU is a complex task considering the multitude of aspects involved in the energy system [70]. There is a high range of uncertainty with the input assumptions as they are exogenously determined in the energy system analysis as also discussed in Section 1.1. Therefore, uncertainties are one of the fundamental aspects needing to be incorporated in the analyses to verify the mitigation options' role based on the technologies' given exogenous techno-economic characteristics. The results of uncertainties surrounding the cost of technologies and renewable potentials in different sectors can give contradicting results [71]. Therefore, uncertainty analysis is a complementary requirement for the transformation pathways during the energy transition as elaborated in Section 1.1.

Although sensitivity analysis is a standard method to analyze the impact of uncertainties to develop decarbonization strategies, there are different approaches available in the literature to consider the uncertainties in the energy system design [72, 73, 74, 75].

Monte Carlo analysis as one of the approaches has been performed in different studies to gain insights from the uncertainties for the energy system's future design. The method was first introduced as an application in the energy system analysis in [76]. UK energy system model was further developed to carry out the Monte Carlo analysis. The aim was to identify if system uncertainties impact the specific carbon price level to deliver the emissions reductions in the long term. The results showed a high probability of achieving the given reduction target at the reference price level in 2050. [77] applied the same method for the economic feasibility of hydrogen fuel cell vehicles. In another study [78], the nuclear technologies' uncertain role was assessed, and early nuclear investments brought higher cost savings to the system. In [79], multivariate regression was performed, and standardized regression coefficients were employed to scale the uncertain input parameters. The results showed that biomass availability, gas prices, and nuclear capital costs were the critical uncertainties to reach the given reduction targets. Monte Carlo analysis does not need alterations in the model structures or mathematical formulations, but the computational burden brings a significant disadvantage for the methods' effective applications. Additionally, short to mid-term hedging strategies are not part of the analysis.

Robust optimization has been performed to assess the uncertainties in the energy system studies as well. Technology cost uncertainty for the French transport sector was evaluated in [80]. Less uncertain technologies were deployed more and differentiated technology mix resulted as an outcome of the analysis. Again, the cost uncertainty with the same approach was studied in [81]. When uncertainty was considered in the optimization function, the system cost increases. Technologies like biofuels were identified as robust technologies according to the findings. Modeling to generate alternatives has been applied in different studies for the uncertainty analysis in addition to the other methods. In [82], the method was used to pinpoint alternative energy scenarios called structural uncertainties for US electric and light-duty transport sectors' future development. The results showed the higher deployment of the technologies, specifically IGCC, biomass, and wind, when uncertainty is considered in the analysis. Similar applications were also seen in other studies [83, 84, 85]. With this method, it is not possible to assess the parametric uncertainties, which are known mainly as the input assumptions to the model. Therefore, the approach's application is limited for the model input assumptions such as cost of the technologies or potentials.

The studies available in the literature with the application of stochastic programming discuss the impact of given uncertainties in the energy system analysis for the system's design as well. Stochastic modeling was applied with the MESSAGE model in [86] to analyze the impact of the technology cost uncertainties. According to their findings, the results became more robust with stochastic programming, although the system cost increased. Stochastic programming application is also seen in a power sector model, OseMOSYS [87], to model policy uncertainties on the electricity market's capacity planning. Various policy scenarios, carbon caps, carbon tax, and renewable portfolio standards were assessed with different policy levels - no policy, weak, moderate, strong, and very strong - and different probabilities. Based on the comparison between the stochastic and deterministic results, decarbonization is delayed in the hedging strategy in the carbon tax scenario. However, in the carbon tax and renewable portfolio standard scenarios, a hedging strategy requires initial actions rather than postponing. Stochastic programming was applied in an integrated assessment model, covering gas and electricity markets in [88]. The aim was to discuss the impact of gas demand uncertainty in other sectors on electricity generation capacities. The results showed that the uncertainty alters the investments in gas-fired power plants.

To identify the near-term hedging strategy considering the fossil fuel prices and biomass import availability in the UK's energy system, a study was conducted with stochastic programming in UK MARKAL in [71]. According to their findings, uncertainty on the fossil prices brings a higher cost to the system than biomass import uncertainty considering the hedging strategy. The uncertainty of oil and gas prices on the energy system development was examined with a multi-stage stochastic optimization of a simple energy system in [89]. They structured the study with a shorter hedging period, 5 years. Therefore, the insights were rather limited from the stochastic modeling. The Indonesian power generation system's expansion planning problem was assessed with a stochastic tree and Monte Carlo simulation in [90]. Incorporating a statistical distribution for the given variables allows the continuous consideration of uncertainties in the system design. To define hedging strategies for the different technology outlooks, the TIAM-World model was applied with stochastic programming [91]. Natural gas appeared as one of the robust technologies in their results, and nuclear power and CCS options were not favorited as robust technologies. Climate targets and CO_2 storage availability uncertainties were studied in another TIAM model, TIAM-ECN, in [92]. With a two-stage stochastic model, deterministic and stochastic results were compared with each other. Their results showed that ambitious climate targets are the decisive factors for the results, and to hedge the reduction target uncertainty, early actions, especially with the CO_2 storage technologies, are necessary.

Key identified gaps included in this thesis in relation to research objective 2

Scenario analysis to identify the role of the technologies

Although various reduction targets have been studied with diverse models, this analysis has not been carried out yet at the EU level, where feedbacks from air pollution control and macro-economic variations together in the energy system are considered. Furthermore, the focus so far for the role of a specific technology in a specific sector. There is still a need to test the cause-effect relationship between the interconnected sectors in the energy system to identify technologies' role considering the dynamics in another sector.

Uncertainty analysis to verify the role of the technologies

The impacts of the many uncertainties around the mitigation technologies' cost, the availability of technologies, demand projections, and GHG reduction targets are discussed in the literature. As discussed with the technology cost expectations, there is no limitation for the data dealt with during the energy system analysis. Since it is not clear how the future will develop, uncertainty assessment is a complementary study to verify the future of technologies and sectoral interactions, considering the feedback from the integrated assessment framework and pathway analysis while considering various GHG reduction targets. Although several uncertainties have been assessed in the existing literature, a study which focuses on a specific sector development such as transport that the mitigation technologies are still in progress in terms of the cost reduction and available potential, as discussed in Section 1.1., in the context of an energy systems analysis is still missing.

1.4 Contribution of this Thesis to Contemporary Research

The limitations of the previous research for integrating air pollution control and macro-economic parameters considering different approaches are systematically discussed in Section 1.3.1. According to these findings, the first research question, in Section 1.2., is revisited to outline the gaps which will be the advancement to the contemporary research as a result of this thesis.

- **Research Question I:** What are the implications of the trade-offs between the energy system transition and environment and economy along the whole transition pathway in the EU?
  - An integrated assessment framework that considers the feedback loops from environment and economy at the same time has not been created before with a soft-link between the relevant models by focusing on the impacts in the energy system.
  - The link with the environmental impacts has not been analyzed at the EU level by taking and not taking into account the health damage costs in optimizing an energy system.
  - A link between an energy system, which has already considered the environmental impacts in the structure, has not been established yet by adapting to macro-economic feedbacks on each energy service demand in the energy system, including residential and commercial sectors.
  - A link between an energy system model and a macro-economic model has not been executed yet, focusing on the electricity sector since most of the macro-

economic models in the literature have a limited technology representation in the electricity sector.
    - The feedback loops' roles from environment and economy to the system's decarbonization have not been analyzed yet.

Based on these gaps identified, this thesis will analyze the trade-offs between environmental and macro-economic aspects and energy system. For this analysis, pollutants and their damage costs will be integrated into a European energy system considering all the sectors and the Member States. The impact of the air pollution control considering and not considering the damage costs in the energy system optimization will be assessed at the EU level with different scenario analyses. In the second step, the link with a macro-economic model will be realized to integrate the macro-economic feedback to the European energy system after including the damage costs. This link will be created through a soft link to provide enough flexibility and transparency to the process, as discussed in Section 1.3. So far, the integration of macroeconomic feedback has been limited to specific sectors. This thesis will consider all the end-user demands defined in the energy system. The chosen macro-economic model will focus on the electricity sector to make sure the feedback from the energy system model to the macro-economic model is properly set, considering that electricity has the most mature decarbonization technologies between the energy system sectors. Additionally, the decoupling of the energy service demands from the economy will be considered within the scope to assess the impacts of such a factor during the iteration process as well as on the final demand figures. Since this link will be created after the integration of air pollution control, first of it is kind, this thesis will internalize both of the feedbacks simultaneously. This thesis will also close an additional gap in the contemporary research by applying the CO_2 decomposition analysis to assess the impact of each feedback on the decarbonization path. The methodology to integrate these aspects are explained in Section 2.3.

The gaps for the scenario analyses to identify the mitigation options' role and their verification are determined in Section 1.3.2. According to these findings, the second research question, in Section 1.2., is revisited to summarize the gaps which will further the knowledge in the contemporary research as a result of this thesis.

- **Research Question II:** What are the key mitigation options' role considering the economic and environmental impacts of the energy transition by taking into account the cause-effect relationships between the interconnected sectors in the energy system and the relevant uncertainties during the decarbonization of the energy system in the EU?
    - Decarbonization scenarios have not been examined yet to test the cause-effect relationships between the interconnected sectors by concentrating on the different technology trends.
    - Such an analysis has also not been carried out yet considering the feedbacks from air pollution and macro-economic variations in the energy system.

- Uncertainty analysis concentrated on a specific sector development such as transport, which ETS does not regulate, has not been carried out yet considering the available mitigation technologies, uncertainties, and different reduction targets in the EU.
- The role of the mitigation technologies in such a sector, transport, based on the cause-effect relationships between the interconnected sectors has not been verified yet.

Based on the missing knowledge in the contemporary research as stated in Section 1.3.2, this thesis will improve the understanding of the role of the technologies through the energy transition in the EU by testing the cause-effect relationship between the interconnected sectors to close the relevant gap. This will be done by developing system-focused analyses of historical trends and technological developments, where feedback from air pollution and macro-economic variations in the energy system are considered as a result of the first research question. Additionally, uncertainties have not yet been analyzed to verify the role of the key technologies on the EU energy system's decarbonization, focusing on a single sector development such as transport. The impact of the learning uncertainty of battery packs in EVs, the uncertainty of biomass availability, and the criticality of these options for transport sector decarbonization considering the policy uncertainty will be analyzed in the EU energy transition within the scope of this thesis. The scenario analysis applied is elaborated in Section 2.5. The methodology for assessing the critical uncertainties in the energy system to verify the role of the technologies is explained in Section 2.6.

1.5 Structure of this Thesis

This thesis's analysis is divided into four parts based on the methods, analyses, and results of the associated 4 different Publications to systematically answer the stated research questions and fill the gaps in the contemporary research mentioned detailed in Section 1.4.

To assess the first research objective in Section 1.2 analytically, a link between an energy system and a health impact assessment model is created as the first step in this dissertation to incorporate the environmental feedbacks into the energy system analysis for the decarbonization paths in the EU. With this link, health damage costs are integrated into the European energy system model's existing structure for air pollution control. The energy system model, which has already adopted the environmental perspective into the structure, is linked to a macro-economic model in the next step as first of its kind. This link is built to reflect the energy transition's macro-economic impacts on the energy system. The links are created with a climate policy scenario. Decomposition analysis is carried out to assess the main drivers for the decarbonization of the energy system as an additional novelty in this thesis. The detailed methodology and findings are elaborated in Publication I. The methodology introduced in Publication I and the damage cost data for the air pollution control is applied to evaluate the interactions between decarbonization targets and air pollution control in Publication II. Their implications on the European energy system are discussed in detail based on two different GHG reduction target scenarios when the health damage costs are part of the energy system's optimization and are not part of the energy system's optimization.

To examine the second research objective in Section 1.2. thoroughly, the integrated assessment framework created in Publication I is applied for scenario analysis to test the cause-effect relationships between the interconnected sectors by identifying the key technologies during the energy transition in Publication III. Uncertainty assessment is carried out in Publication IV to verify the findings in terms of technology development and different GHG reduction targets for the uncertainties associated with it.

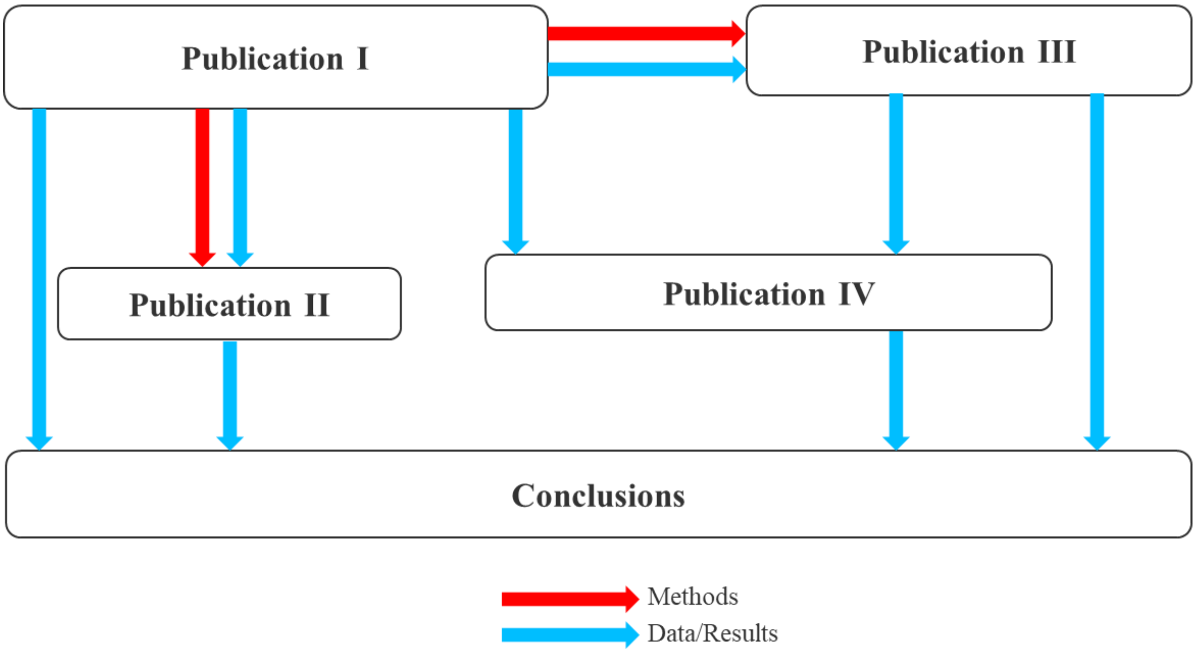

Figure 1: Relative relationship between Publications based on the research questions

Figure 1 depicts the relationship between Publications founding this thesis as explained. The arrows illustrate the use of methods (in red color) and results and/or data (in blue color) between Publications. Publication IV uses the results to structure the analysis acquired in Publications I and III. Publication III is informed by the methods applied in Publication I and uses the data for further assessment. Publication II applies the methodology introduced in Publication I. The integrated assessment framework created in Publication I is applied for scenario analysis to test the cause-effect relationships between the interconnected sectors by identifying the key technologies during the energy transition in Publication III. To verify the findings in terms of the technology development and different GHG reduction targets for the uncertainties that they are associated with, uncertainty assessment is carried out in Publication IV.

The remaining part of the thesis is structured as follows: Chapter 2 describes the methodological background, including the models, the links between the energy system model and other models, and the uncertainty assessment. Chapter 3 presents the individual Publications. The research and the findings are summarized in an integrated way in Chapter 4. Finally, Chapter 5 discusses the findings and limitations and provides the outlook for future studies.

2 Methods

This chapter explores this thesis's underlying methodology, including describing the models applied, their interactions, and additional methods such as stochastic programming to address the research questions stated in Section 1.2. As explained in Section 1.1., energy system models are the tools to be applied for the energy system analysis.

In Section 2.1., a general overview of the energy system models and studies is provided. In Section 2.2., the TIMES model generator is explained. The general model structure of TIMES PanEU is introduced in Section 2.3. The development of the integrated assessment framework through the links with the other models is presented in Section 2.4. This framework must fill the relevant gaps identified as relevant to the first research question stated in Section 1.4. to improve the existing knowledge with the energy transition. In Section 2.5., the scenario analysis, which is applied to the integrated framework to identify the key mitigation options considering the cause-effect relationship between interconnected sectors, is described to further the existing knowledge around the second research question in Section 1.4. In the last section of this chapter, Section 2.6., the methodology is demonstrated to assess the energy system models' critical uncertainties to verify the role of the key technologies specific to the transport sector. The motivation for applying the chosen method for the uncertainty analysis, stochastic programming, is also explained in this section.

2.1 Energy System Models

Energy systems are defined as a process chain from the extraction of primary energy to the final energy to supply services and goods [93]. Accordingly, energy system analysis can be described as a methodology to measure technologies' impact from primary energy extraction and the materials-usage to fulfill the energy service demands [94]. Energy system analysis concentrates on the entire system and the interactions between the different parts of the energy system instead of a single sector such as electricity or a single technology [5]. The energy system analysis's main objective is to provide the insights to make decisions for energy-related issues. These insights also include the assumptions that need to be made during the analysis. Recently, energy system analysis has been applied in different studies to address the topics around climate change mitigation [95, 96].

Energy system models have been developed as a tool to be applied for different analyses to address the specific research questions and the topics such as climate mitigation with energy system analysis. According to a systematic review carried out in [97], there are mainly 4 different types of models to be used in the energy system analysis: bottom-up energy system models, input-output models, top-down macro-economic models, and environmental models. Input-output and macro-economic models focus on the interdependencies between the economy and other sectors. Input-output models have a bottom-up representation of the economy, and it is possible to analyze the relationship between different economic sectors in terms of output and input relationship. Macro-economic models assess the macroeconomic impacts from deviations in prices, assets, and productivity. They enable analyzing the impacts of various political interventions on macro-economic indicators, such as GDP growth, sectoral gross value added (GVA), employment, and competitiveness [98]. Environmental models are mainly applied for the assessment of the environmental impacts of technologies and policies Energy system models have a bottom-up structure. The energy system models describe each process with a technology focus. They are classified as simulation and optimization. The optimization models aim to have the cost-optimal system considering the given constraints. On the other hand, simulation models require a share of each utilized technology as exogenous factors. They intend to reproduce the expansion in each sector [99]. Bottom-up energy system models contain the detailed representation of the entire energy system by encompassing all the required technology options for the energy system's future from primary energy to final energy service demand. Therefore, to analyze the required transition in the energy system in the EU's context considering the associated direct costs as described in Section 1.2., it is vital to apply a bottom-up energy system model for such research.

2.2 The TIMES model generator

As explained in Section 2.1, between the existing energy system model structures, the bottom-up partial equilibrium energy system model is chosen to be employed in the scope of this thesis. An energy system model, which has the detailed representation of the technologies available today and for the future and can integrate the air pollution control as well as macro-economic impacts and deliver uncertainty assessment to verify the role of the critical mitigation technologies, is required to address the research questions stated in Section 1.2.

MARKAL is a model generator that has been most widely applied in energy system studies as an energy system model [73]. Another optimization model was added to the ground structure of MARKAL, which is called EFOM (Energy Flow Optimization Model). With this development, the existing model generator has grown into a new one called TIMES (the Integrated MARKAL-EFOM System).

TIMES is chosen as a model generator to be applied in this thesis since model generator has already been applied in similar energy system transition studies [5, 69, 96, 99, 100] and has the entire energy system in the main structure. Additionally, it is possible to integrate the air pollution control via damage costs into the optimization function and carry out the uncertainty assessment via the different functions [101].

TIMES is a model generator for bottom-up energy system models developed within the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) [102]. Here, the optimization problem can be modeled as a linear optimization problem (LP) or a mixed-integer optimization problem (MIP). In TIMES, there is a separation between the user-specific model structure (represented as the reference energy system RES), the data, the mathematical formulation of the constraints, and the solution procedure [101]. The user creates an energy system model employing a data management system (VEDA-TIMES) [103], from which the user-specific model structure and input data are passed to TIMES and converted into mathematical equations based on the algebraic modeling language GAMS [104]. Here, different solution algorithms are provided to solve the mathematical optimization problem.

$$\min \sum_{j=1}^{n} i_j * y_j \qquad \text{Eq.2-1}$$

The objective function in TIMES involves minimizing the total system cost while satisfying all constraints (Equation 2-1). The model generator's overall objective is at minimum overall costs to supply a set of (exogenously specified) energy-service demands in different end-use sectors. The total annual energy system costs include investment costs, annual fixed operation costs, variable operation costs, net export costs (in multi-regional models), and costs related to commodity flows. In Equation 2-1, i_j refers to the specific costs of the decision variables y_j. The detailed illustration of Equation 2-1 can be found with all the relevant parameters and explanations in [105].

A TIMES model's basic structure is represented by the mapped energy system's structure with its regional and temporal resolution. Here, any number of regions with an individual temporal resolution, topology, investment options, and scenarios can be defined. The time horizon, i.e., the number of periods considered and their respective length and the temporal resolution within a year, can be chosen flexibly. A period can consist of several years, whereby each period is represented by a representative year (milestone year). Four levels are available for the temporal structure within a year [101]: ANNUAL, SEASON, WEEKLY, DAY NITE.

Figure 2 shows an example structure for intra-year temporal resolution when using all four levels in TIMES. Here, each time segment's duration is given as a fraction of a year (G_YRFR) [101].

The following abbreviations applied here:

SR: Spring
SU: Summer
FA: Fall
W: Winter
WD: Weekday
WE: Weekend
D: Day
N: Night

The duration of all-time segments on a level must add up to one. The ANNUAL level represents the representative supporting year, and the SEASON level represents the subdivision of a year. In the present example from Figure 2, a year is divided into four seasons (R, S, F, W). On the WEEKLY level, all-time segments that lie under a common node must represent a week. That means, here, the subdivision of a week is represented (in the example division of a week into the time segments weekday WD and weekend WE). On the DAYNITE level, all-time segments that lie under a common node must represent a day (in the example, division of a day into the time segments Day D and Night N). The time segments in a model with, e.g., hourly resolution (8760 h consecutive) must be defined on the SEASON level. In general, not all levels need to be used when choosing temporal resolution and time segments [101].

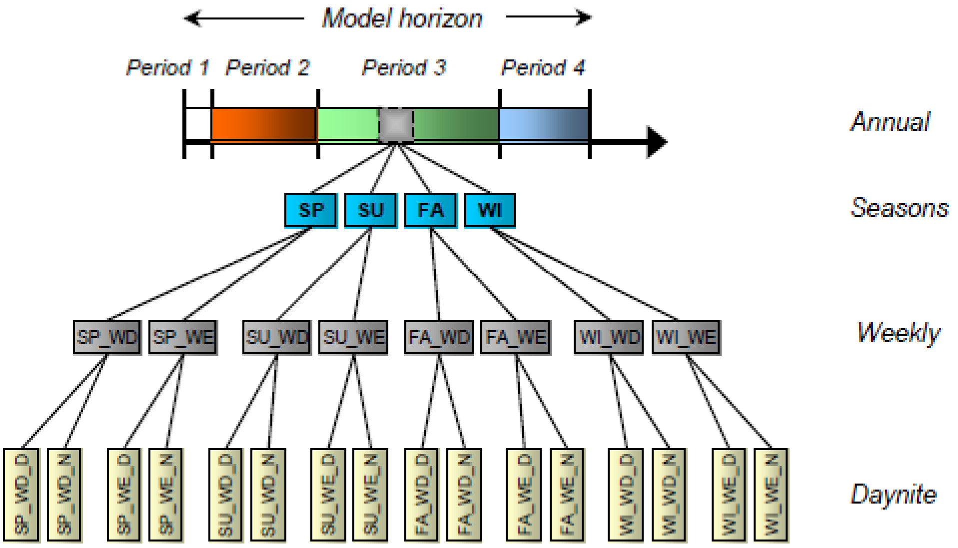

Figure 2: Example of a time slice tree [102]

The energy system's topology is called the reference energy system and is represented by a network of interconnected processes by commodity flows. In this context, processes represent technologies (e.g., power plants or end-use devices) that are interconnected via their input and output goods (commodities) through commodity-flows [101].

The topology of an existing energy system with the existing technologies is defined for a selected base year. Investment options can be defined for the base year as well as for subsequent future periods. Many linear restrictions are stored in TIMES, the most important of which are presented below in their basic structure. For the relationship between activity and capacity of a process, the activity must be smaller than the capacity in each time segment [101, 106]:

$$
\begin{aligned}
&EQ\_CAPACT: \\
&\quad VAR\_ACT(r,v,t,p,s) \leq (VAR\_NCAP(r,v,p) + NCAP\_PASTI(r,v,p)) * \\
&\quad CPT(r,vt,p) * AF(r,v,t,p,s) * PRC\_CAPACT(r,p) * G\_YRFR(r,s) \quad \forall\, r,v,t,p,s
\end{aligned}
\qquad \text{Eq.2-3}
$$

Where:

VAR_ACT:	*Activity of the process*
PRC_CAPACT:	*Ratio of activity and capacity of a process*
VAR_NCAP:	*New installed capacity*
NCAP_PASTI:	*Inventory capacity*
G_- YRFR:	*Share of a time segment in a year*
AF:	*Availability of the process in a time segment*

CPT: *Proportion of the installed capacity of a process that is still available according to its lifetime is still available*
r: *Region*
v: *Year of commissioning*
t: *Current period*
p: *Process*
s: *Time segment*

Individual processes are each assigned a capacity and an activity in TIMES. For a standard process, the parameter PRC_CAPACT specifies the maximum amount of energy that the process can provide (output-related) or consume (input-related) per unit of capacity if it is operated at full load within the entire year. For the commodity balance, in general, simplified form applies [101, 106]:

$$EQ_{COMBAL}:$$
$$\sum_{p=1}^{k}\sum_{v=1}^{t}(VAR\_FIN(r,v,t,p,c,s) - VAR\_FOUT\ (r,v,t,p,c,s)) \leq 0\ \ \forall\, r,t,c,s$$

Eq.2-4

Where:

VAR_FIN: *Input flow of a commodity.*
VAR_FOUT: *Output Flow of a Commodity*
r: *Region*
c: *Commodity*
v: *Commissioning year*
t: *Current period*
p: *Process*
k: *Run variable for process p*
s: *Time segment*

Any number of internal and external model regions can be defined in a TIMES model. Internal regions are regions for which a separate reference energy system is defined by the user (processes and commodities), i.e., whose energy system is to be modeled. External regions serve as a source or sink for commodities. External regions can be used to model an external exchange of commodities employing an exchange process (export EXP or import IMP) [101]. Exchange processes for commodities can also be defined for TIMES internal regions.

The individual TIMES internal regions can be modeled with different temporal resolutions. That is, a separate sub-annual tree structure can be defined for each model region. The modeling of bilateral exchange processes is done with a different temporal resolution of two regions via the parameter IRE_TSCVT. This parameter is used to specify the proportion of time segments of one region to the other region's time segments [101].

The reference energy system describes the existing energy system for the base year of a region. User-defined restrictions, called user constraints, can be used to represent additional linear constraints and scenarios specified by the user in the model. In general, TIMES distinguishes between three types of user constraints [101]:

- Left-hand side (LHS) user constraints,
- Dynamic user constraints,
- Growth constraints.

The standard LHS user constraints have the following structure [101]:

$$\sum_{r=1}^{n}\sum_{t=1}^{l}\sum_{s=1}^{m}\big(LHS(r,t,s)\big) \quad <=> \quad UC\_RHS \qquad \text{Eq.2-5}$$

The special case for one model region, one period, and the one-time segment is [101]:

$$LHS\ (r,t,s) \quad <=> \quad UC\_RHS(R)(T)(S) \qquad \text{Eq.2-6}$$

Where:

l:	*Variable for period t*
m:	*Variable for time segment s*
n:	*Variable for region n*
r:	*Region*
t:	*Period*
s:	*Time slice*
LHS:	*Left side of the restriction (variables with coefficients)*
UC_RHS:	*Right side of the restriction (constant), formed from the sum overall regions, model periods, and time segments*
UC_RHSRTS:	*Right side of the restriction (constant), formed for one region, one-time segment, one period.*

The left side of the constraint (LHS) can be formed from the following variables: Activity UC_ACT, Commodity flow UC_FLO, Import/export of a commodity UC_IRE, Commodity production UC_COMPRD, Commodity consumption UC_COMCON, Commodity consumption net UC_COMNET, Activity cumulative UC_CUMACT, Commodity flow cumulative UC_CUMFLO, Commodity consumption net cumulative UC_CUMCOM, New investment UC_NCAP, and Capacity UC_CAP. User-defined constraints can be defined for any regions, periods, and time segments. A link between periods or time segments can be allowed via dynamic user constraints [101, 107]. Growth constraints are a particular case of dynamic constraints used to specify growth rates [101]. More detailed information about the user constraints and the TIMES model generator's applied equations is available in [106].

The TIMES model generator includes different functions to consider additional parameters during the optimization. Implementation of an endogenous learning curve with mixed-integer programming, a climate module, the stochastic programming extension, the lumpy investment extension, elasticity implementation, and employment of damage cost is extended functions in TIMES. Additional parameters need to be defined as supplementary to the existing input assumptions to utilize the function. For example, to employ the damage costs, the pollutants' emission coefficients must be incorporated in the first step and followed by their damage costs. The damage costs can be considered in the optimization function. This means that the model also optimizes the cost of the pollutants, or they can be calculated without including the costs in the optimization. The relevant equations can be found in [101] for the additional functions.

2.3 General Model Structure of TIMES PanEU

As the cause-effect relationships between interconnected sectors are within this thesis's scope, an energy system model covering the entire energy system from supply to end-users is essential, as explained in Section 2.1 and Section 2.2. Therefore, the TIMES is chosen as a model generator that includes the complete energy system and can conduct uncertainty assessment with stochastic programming to provide the research question's findings around the uncertainties in the energy system. Since this thesis aims to assess the transformation pathways in a sustainable European energy system by integrating air pollution control and macro-economic impacts, TIMES PanEU is opted as an energy system optimization model to answer the research questions stated in Section 1.2. TIMES PanEU, which has already been applied and reviewed in many studies focusing on the energy system transition [95, 108], can fulfill the requirements to conclude the system interactions between the interconnected sectors as well as the Member States.

TIMES PanEU covers the European Union countries as well as Norway and Switzerland, and each country represents a single region in the model. The modeling horizon spans from 2010 to 2050, split into 5 year-time steps. A year is divided into 12 time-slices, 4-seasonal and 3-day levels (day, peak, and night). Greenhouse gas emissions (CO_2, CH_4, N_2O) are included in the model. The reference energy system includes all relevant energy, material, and emission flow from the primary production to meet each region's energy service demands defined in the model [101]. With its sectoral structure and spatial resolution, TIMES PanEU provides the possibility to address the sector integrations and interactions between the Member States, which is essential, for instance, concerning the domestic source potentials such as biomass. These sources need to be evaluated at the sectoral and country-level. The interactions between sectors and the possibility of trade between the Member States also should be considered. Several technological options are modeled to enable such integrations and interactions between different parts of the European energy system. Parameters such as investment cost, efficiency, variable operation and maintenance cost, fixed operation and maintenance cost, fuel cost, emission factors, and availability factors are required to model a technology [109].

Primary energy sources are modeled according to country potentials and trade possibilities from the neighboring countries. Cost potential curves are defined for each source, such as crude oil, natural gas, coal, lignite. The World Energy Outlook 2016 prices [110] and average country mining costs are taken as references to determine the cost figures. Various bioenergy carriers are included by considering the country's potential and their costs. No constraints are considered for biomass trade between the Member States. Land availability for biomass cultivation is given in the model based on [111]. Moreover, other conversion technologies such as refineries, gasification, and Power-to-Gas are part of the model [102].

In the electricity sector, the electricity supply at various voltage levels is modeled with the relevant technologies. Large central power plants feed to the system's high voltage grid, while decentralized generation such as PV systems feeds to the medium and low voltage grids. The technologies that exist at the start of the modeling period and those considered future options are classified according to the input fuels and technology type. They are aggregated by power plant type. New technologies such as electricity storages, hydrogen technologies, and CCS technologies are modeled as investment options during the time horizon. The availability of certain technologies such as CCS is determined according to the expected availability date [112]. Cogeneration plants (CHP) for centrally supplied district heat are given as a choice in the model to provide both electricity and heat. Power-to-Heat technologies, together with heat storages, are applied in the public heat supply [112].

The industrial sector is divided into energy-intensive and non-energy-intensive industries. Energy-intensive industries include iron and steel, aluminum, copper, ammonia, chlorine, cement, lime, flat glass, and paper. In contrast, the non-energy intensive industries include other non-ferrous metals, other chemicals, other non-metallic minerals, food and tobacco, and other industries. Industrial auto producers are also modeled [113]. There are two approaches to model the energy inputs within the industrial sector of TIMES PanEU - process-oriented and application-oriented modeling. The process-oriented approach is applied to model the energy-intensive industries, while the application-oriented is used for the non-intensive industries. In process-oriented modeling, the demand for certain production goods must be met in terms of physical quantities (Mt). This demand is given exogenously to the model. Various technologies with different technical and economic parameters are available at different production stages to meet the energy service demand. The technology choice is a result of optimization. The modeling of non-energy-intensive industries is based on energy application types and requires different types of useful energy. Therefore, the demand refers to an amount of energy (i.e., in PJ) instead of physical quantities. The useful energy demand of the non-energy- intensive industries is divided into different groups according to different types of application of industrial energy use. These include thermal applications (space heating, hot water, process heat, steam), electric motor applications (pumps, compressed air, fans, refrigeration, other motor applications), and other applications such as lighting, electrochemical conversion processes, and other applications. The starting point for this modeling is the results of the analysis of the industrial sector. To satisfy the demand for useful energy, the model has different processes with different efficiencies and costs at its disposal. For example, boiler plants or industrial CHP, based on different fuels, are available for heat supply [113].

In the household, commercial, and agriculture segments, the energy service demands are disaggregated according to different sectors. Various technologies, aggregated according to technology type and energy carrier, are implemented to provide the energy service demands. There is a further disaggregation of household energy service demands to space heating single-family urban and rural, space heating multi-family, water heating, space cooling, lighting, cooking, refrigeration, clothes washing, drying, dishwashing, other electric, and other energy. The process to supply the agriculture demand is defined as one general process. Commercial energy service demands are also further disaggregated to space heating large and small, space cooling large and small, lighting, cooking, refrigeration, public lighting, other electric, and other energy [100]. The underlying assumptions of the existing energy service demand figures according to disaggregation in TIMES PanEU are consistent with the socio-demographic assumptions of the EU Reference Scenario [20]. Non-energy GHG emissions from the agricultural sector are modeled, and certain mitigation technologies to cover the Paris Agreement's scope. These emissions are caused by fertilizers and livestock (manure management, enteric fermentation).

The transport sector is disaggregated according to transportation modes. Car transport demand is further disaggregated as short and long-distance. Dimethyl ether, diesel, gasoline, gas, LPG technologies are available as conventional ones in the existing structure. Electric cars and hybrid technologies with gasoline, diesel, gas, and ethanol options are also implemented as mitigation technologies. As additional technology options to fulfill the model's car transport demand, ethanol, biodiesel, and hydrogen cars are offered. Ethanol, biodiesel, and hydrogen cars are offered as technology options to fulfill the model's car transport demand. Bus transport demand is further disaggregated as intercity and urban. Like car transport, technologies with gasoline, biodiesel, ethanol, gas, hydrogen are available for this transport mode. The electric vehicle option is available for the urban mode together with diesel hybrid. Due to the urban mode's availability, electric vehicles are modeled for this transport model [100]. Other transport demands are defined as motorcycles, trains (passenger and freight), light and heavy-duty transport, air traffic (international and domestic), and waterborne (international and domestic). Passenger transport is modeled in passenger-km (Pkm) units, whereas freight transport is modeled in ton-km (Tkm). Each vehicle technology based on the different energy carriers is modeled for the demand categories mentioned above. Hybrid technologies, biofuel technologies, and electric vehicles are available for the road transport modes as mitigation options.

Mitigation options are also modeled to decarbonize the aviation and navigation sectors. These transportation modes are implemented as generic processes in TIMES PanEU, which means there is no defined investment cost. The system's cost optimization only depends on the cost of the fuel and the CO_2 emission coefficient. The milestones in terms of technological improvement are defined to decarbonize these sectors in [28]. These milestones are considered in TIMES PanEU as annual constraints to the availability of the technologies. In aviation, bio-kerosene for domestic and international flights is defined as an option starting from 2015. Biodiesel is given as an option for domestic flights starting from 2025 and international flights from 2035. A maximum of 10% of the domestic flights demand can be met through electricity and 10% again through hydrogen. These levels increase to 15% electricity and 20% hydrogen by 2050. These values are set as a maximum of 5% for the share of electricity and hydrogen in the energy carrier mixture for international flights. The share of hydrogen is increased to 10% in 2050. In navigation, LNG, biodiesel, and biokerosene are defined as options starting 2025, in line with the milestones in [28]. LNG prices are based on the World Energy Outlook [110]. Electricity and hydrogen are given as options starting from 2035. The shares for electricity and hydrogen are kept at a maximum of 10% in the international and domestic supply energy mix. Electricity is increased to 50% in 2050.

Various assumptions are used in diverse parts [114, 115, 109, 116] of the analysis in this thesis. The study-specific assumptions are given in the relevant publications.

2.3.1 Calibration of TIMES PanEU

Before initiating the work to build the integrated assessment framework, the existing model structure of TIMES PanEU was validated. According to [117], model verification is defined as "ensuring that the computer program of the computerized model and its implementation are correct." Model validation means that "a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application" [117]. The model was calibrated based on the historical data in 2015 to validate the model. Since the base year of the existing TIMES PanEU is 2010, 2015 is the first period to be calibrated according to the 5-year time-step structure. Recent historical trends, projections by the other models generally guide the calibration process [118]. The calibration and validation of the model in 2015 are essential to creating the integrated assessment framework to integrate the air pollution control and macro-economic impacts. There are different techniques available for the calibration of the energy system models. According to different energy carriers, technology-specific bounds on capacity or the bounds on energy consumption are widely applied techniques to calibrate the models [118]. However, during the calibration process, it is also critical to consider that if the model is overly constrained, it may cause some computational problems and take the model's flexibility to produce the results in the upcoming periods [119]. According to this, the calibration process is carried out on the energy carriers to match them with the historical trends for the electricity generation and the final energy consumption of the sectors included in the model. Considering that the model should not be over-constrained to match the specific numbers, 15% of the error margin is determined as a validation criterion.

The calibration commenced in the electricity sector calibrated according to 2015 statistical values [20]. Baltic and Balkan regions are given priority over the other Member States in the model. Those countries have a relatively smaller electricity system than other countries in the EU. The calibration with the electricity exchange in 2015 between the other Member States could be challenging due to their relatively lower existing electricity capacity. Installed lignite capacities, coal, and hydro were also calibrated with their realized generation in 2015 in Bulgaria, Croatia, Hungary, Slovenia, Romania, Estonia, Finland, Latvia, and Lithuania. Decommissioning curves of existing conventional power plants are also aligned with the country plans of those countries. The nuclear power plant availability factors are calibrated in Bulgaria, Hungary, Slovenia for 2015 as those power plants performed distinctively to 2010. Solar and wind power plants and their capacities were adjusted according to the given statistics. According to energy carriers, insights from the calibration and validation of TIMES PanEU and their error margins are given in Appendix A 1 and Appendix A 2 for selected countries, Croatia, and Hungary.

After this, electricity exchange capacities and the amount of electricity traded between countries are validated. The data is taken from [120] for Baltic regions for 2015. Additionally, scheduled exchange capacities at the borders are also implemented according to these capacities' expected commissioning dates. Comparison between the statistical values and model results of the trade amounts for the selected regions in 2015, Finland and Latvia, are given in Appendix A 3 and Appendix A 4.

The calibration effort continued with the electricity sector in other countries. Nuclear power plant availability factors are adjusted in Belgium, France, Germany, Spain as some of these capacities went through maintenance periods and performed with lower capacity factors than in 2010. Solar and wind generations are calibrated based on the realized values in 2015 [20] also in countries such as Italy and Portugal. Electricity generation from hydropower plants and pump storages in the countries with a higher share of hydro generation, such as Sweden and Austria, is also calibrated according to statistical values in 2015. The comparison between the statistics and TIMES PanEU results are presented for the selected regions, Italy, and France, in Appendix A 5 and Appendix A 6.

Calibration is then conducted in other sectors such as residential, commercial, and agriculture. The shares of the energy carriers are calculated based on the statistical values, and these shares are implemented into the existing structure of the model by user constraints to follow the same trend with the energy consumption values according to the energy carriers. These bounds are relaxed through the model horizon to provide more rigidity during the optimization. Instead of giving the absolute bounds to the model, these lower and upper share bounds are implemented to provide enough flexibility to the model considering the error margin. These bounds are relaxed through the model horizon to provide more rigidity during the optimization. The comparisons between the selected regions' statistical values and model results for this work can be found in Appendix A 7 and Appendix A 8.

2.4 Development of an Integrated Assessment Framework

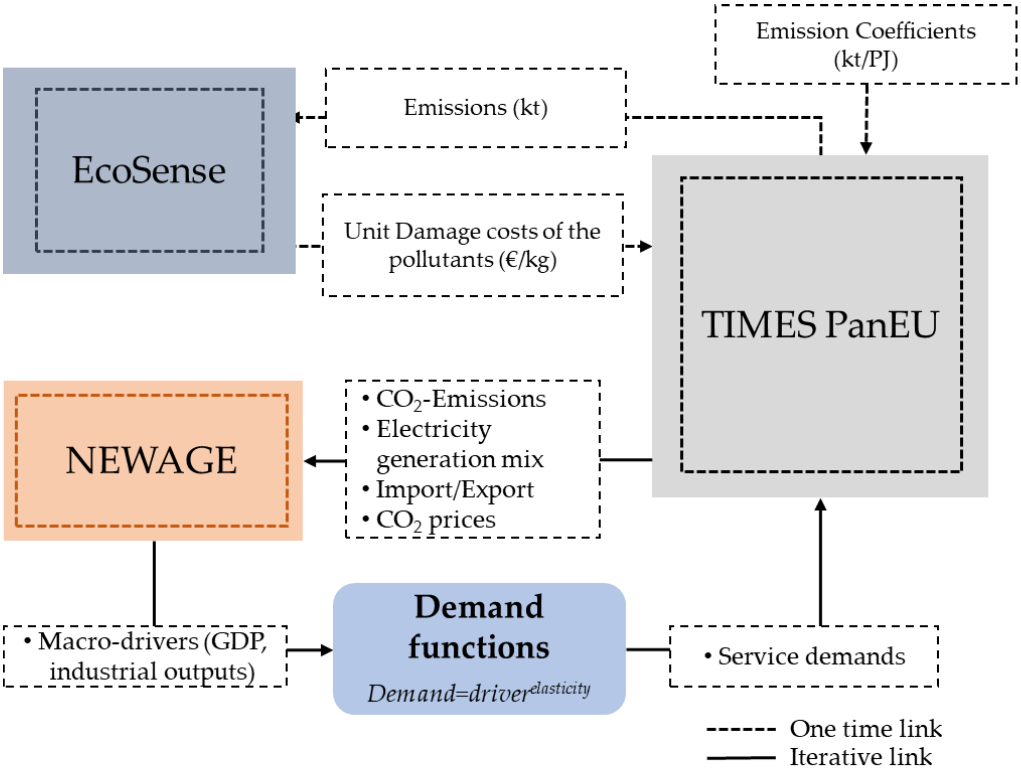

Figure 3: Integrated Assessment Framework - links between the models [114]

In this section, the methodologies to integrate the environmental impacts through the air pollution control and macro-economic effects of the energy system transition into the energy system as relevant to the first research obejctive in Section 1.2. are presented. The section is divided into two parts to explain the development of the integrated assessment framework based on the existing structure of TIMES PanEU, as explained in Section 2.3. In Section 2.4.1, the integration of air pollution control into the model is explained, and the macro-economic impacts incorporation follows it in Section 2.4.2.

2.4.1 Integration of Air Pollution Control

The first step of creating an integrated assessment framework structured around the energy system model, TIMES PanEU, is to incorporate air pollution control into the energy system model's existing structure to address the first research objective stated in Section 1.2.

There are mainly two methods that have been applied so far in the literature to implement air pollution control in the energy system models, as discussed in Section 1.3.1. One method is to implement the emission bounds for the local air pollutants, namely SO_2, NO_x, CO, NMVOC, NH_3, $PM_{2.5}$, $PM_{10,}$ and analyze the system's modifications based on the reductions in air pollution [47, 48, 49]. This method does not articulate a cost-optimal energy system since reduction with the pollutants occurs in the system due to a constrain but not due to additional cost-burden. The aim of integrating air pollution in this thesis's scope is to have cost-optimal mitigation and, based on this cost-optimal solution, to assess how the energy transition is affected. In this way, social welfare can be also maximized in the energy system considering the society aspect. Therefore, the integration of the damage cost into the energy system is chosen as a method to obtain a cost-optimal energy system that considers the environmental impacts from the cost perspective and the reduced emission levels to maximize the social welfare.

The emission coefficients are integrated to incorporate the damage costs into the model as a first step. After this, EcoSense is chosen as an impact assessment model to simulate and estimate health impacts due to air pollution across Europe considering the established impact pathway approach since this approach links changes in national emissions of the main air pollutants (SO_2, NO_x, CO, NMVOC, NH_3, $PM_{2.5}$, $PM_{10,}$) to health impacts across Europe.

The impact pathway approach established in the ExternE project series is the approach in Ecosense to estimate the health impacts due to air pollution [121]. An atmospheric dispersion model is integrated with epidemiological studies and an economic assessment of the effects to calculate these impacts [122, 123]. First, a parameterized version of the EMEP/MSC-W model [124, 125] is applied to estimates changes in concentration levels of Ozone, NO_2, and particulate matter ($PM_{2.5}$ and PM_{10}, including primary and secondary particles) attributable to changes in national emissions on a 0.5° × 0.25° grid covering Europe and neighboring regions in Africa and Asia. Based on concentration-response functions recommended by the World Health Organization (WHO) [126], stating the change in relative risk of a specific outcome (inter alia increased mortality, hospital admissions, and workdays lost) due to an increase in exposure to air pollution, additional cases related to the original changes in emissions are then estimated by also considering detailed population data and background disease rates [127]. The population data in EcoSense considers the spatial distribution of the high-resolution population density grid for Europe [128] as well as country-specific age structures and population projections based on UN data. Finally, the different health impacts are aggregated in monetary values by applying a willingness-to-pay approach for impacts on mortality ("Value of Life Year") and standard prices for all other impacts. EcoSense applies monetary values based on the HEIMTSA/INTARESE case study, [123] with gaps filled by considering values from [128]. By relating the absolute costs of an emission scenario to the respective amount of emissions, unit cost factors can also be estimated. This application of the model is described in more detail in [129].

Before initiating the link between the two models, TIMES PanEU and EcoSense's assumptions are aligned for population growth and general socio-economic developments. The emission coefficients kt/PJ) of air pollutants (SO_2, NO_x, CO, NMVOC, $PM_{2.5}$, $PM_{10,}$ NH_3) are updated in TIMES PanEU to reflect the latest developments and emission standards induced by the Clean Air Policy Package [130]. These coefficients are disaggregated according to sectors, regions, technology, and fuel types in TIMES PanEU [129]. Based on these coefficients, TIMES PanEU provides to EcoSense sector- and country-specific total emissions (kt) for each pollutant. By utilizing the data from TIMES PanEU, EcoSense calculates unit health damage costs (€/kg). These are disaggregated according to different pollutants without sectoral decomposition and fed back to TIMES PanEU.

The unit health damage costs are implemented as an additional parameter, and the total health damage costs are calculated in the model according to the following equations [131]:

$$\mathrm{DAM}\ (\mathrm{EM}) = \alpha * \mathrm{EM}\ (\beta + 1) \qquad \text{Eq.2-7}$$

Where:

EM (kt): *the emission in the current period,*
DAM (EUR/kt): *the health damage cost in the current period,*
$\beta \geq 0$ *the elasticity of the marginal health damage cost to amount of emissions,*
$\alpha > 0$ *calibrating parameter, which may be obtained from dose-response studies that allow the computation of the marginal health damage cost per unit of emission at some reference level of emissions.*

If the marginal cost at the reference level is denoted with MC_0, the following holds:

$$\mathrm{MC}_0 = \alpha * (\beta + 1) * \mathrm{EM}_0\ (\beta) \qquad \text{Eq.2-8}$$

which is what is calculated by EcoSense according to the link between the models.

When there is no elasticity factor assumed (β=0), i.e., when there is a linear relationship between health damage costs and amount of emissions, the first equation can be simplified as follows:

$$\mathrm{DAM}\ (\mathrm{EM}) = (\mathrm{MC}_0 * \mathrm{EM}_0) * \mathrm{EM} \qquad \text{Eq.2-9}$$

The cost figures (MC_0) are calculated for each region in TIMES PanEU according to milestone years. The range of cost figures according to countries and sector disaggregation is available in [129].

An iteration between TIMES PanEU and EcoSense is not required for the analysis in this thesis. There are not any feedbacks to be iterated between the models. Due to the linear relationship between the total health damage costs as calculated by EcoSense and the total emissions, the unit costs are independent of the absolute amount of emissions and climate mitigation policies, which means that the values are scenario independent as well, and the marginal damage costs are constant in different scenarios [114].

The health damage costs can be used for two types of assessments in energy system modeling [114]:

- To provide an exogenous economic evaluation of the health damages by the energy system, without any feedback to the cost optimization function (ex-post);
- To study how the optimal energy supply mix would change if health damage costs were internalized as part of the cost optimization function (ex-ante), which would correspond to a scenario in which air pollutants' health damage costs are considered in the energy system design as additional decision variable and specific costs in Equation 2-1, as described in Section 2.2.

2.4.2 Integration of Macro-Economic Impacts

After integrating air pollution control through damage costs, the second step is to consider the feedback from the economy due to the energy transition to address the first research objective stated in Section 1.2. As discussed in Section 1.3.1, various methods have been applied so far for this purpose. Between the existing methods, the soft-linking method with a macro-economic model is chosen in this thesis considering the advantages that the soft-linking brings to the process as elaborated in Section 1.3.1.

The existing applications for such a link between an energy system model and a macro-economic model are mainly realized by matching the sectoral energy profile based on the energy system model results. These profiles were given as an input to the macro-economic model [50, 51, 65]. Since the technology availability was generally different between the two models in the energy system sectors, the set of assumptions were necessary to have a suitable match. Additionally, so far, there have been missing energy service demands such as residential heating, on which the economy's feedback has not reflected through the energy transition.

In this thesis, unlike the contemporary research, the electricity sector is chosen to be coupled between the two models additional to energy service demands. The electricity sector is selected since the most mature mitigation options for the system's decarbonization are available in this sector. The direct use of renewable energies is somewhat limited in other sectors; only with biomass and solar. Decarbonization scenarios for the other sectors mainly also rely on electrification [3]. Additional novelty aimed in this thesis by creating such a link further to the air pollution integrated to the optimization is integrating the economic feedback into all the energy service demands, including residential heating as elaborated in Section 1.4. Considering these two main points further to the air pollution control, the global computable general equilibrium (CGE) model NEWAGE (National European World Applied General Equilibrium) is chosen to incorporate the feedback from macro-economic variables on the energy service demand development in TIMES PanEU, since NEWAGE has a detailed electricity sector modeled. NEWAGE has already been applied and reviewed in different studies to analyze the macro-economic changes [98, 132, 133, 134]. This implementation aims to alter the decision variables x_j in Equation 2-1, as given in Section 2.2, by integrating the economic variations due to the decarbonization in the energy system on the energy service demands. The available sectors in the existing structure can provide the inputs for the demand developments of all the energy service demands, including residential heating in TIMES PanEU, as given in Table 1.

Table 1: The sectoral match between TIMES PanEU and NEWAGE [114].

TIMES PanEU	NEWAGE
AGR	Agriculture
Commercial Cooling large	Services
Commercial Cooking	Services
Commercial Cooling small	Services
Commercial Heating large	Services
Commercial Heating small	Services
Commercial Lighting	Services
Commercial Other electricity	Services
Commercial Other energy	Services
Commercial Public lighting	Services
Commercial Refrigeration	Services
Commercial Water heat large	Services
Commercial Water heat small	Services
Aluminum	Non-ferrous metal
Ammonia	Chemistry
Other chemical	Chemistry
Chlorine	Chemistry
Cement	Non-metallic minerals
Copper	Non-ferrous metal
Food and Tobacco	Food and Tobacco
Glass Flat	Non-metallic minerals
Glass Hollow	Non-metallic minerals
Iron and Steel	Iron and Steel
Lime	Non-metallic minerals
Other non-ferrous metals	Non-ferrous metal
Other non-metallic minerals	Non-metallic minerals
Other industries	Rest of Industry

High Quality paper	Paper Pulp Print
Non energy consumption chemicals	Chemistry
Non energy consumption others	Non-metallic minerals
Other Sector Consumption	Services
Other electricity	GDP
Road Transport (Short & Long Distance)	Net Income
Motorcycle	Net Income
Bus / Train (Public Transport)	Transport
LKW (Freight)	Transport
Rail Freight	Transport
Aviation (Internal/External)	Transport
Navigation (Internal/External)	Navigation
Residential Space Heating Multi, Urban, Rural	Utility
Residential Space Cooling Multi, Urban, Rural	Utility
Residential Water Heat	Utility
Residential Cooking	Utility
Residential Cloth Washing and Drying	Utility
Residential Lighting	Utility

In NEWAGE, the world is divided into 18 regions, and production is split into 18 sectors. Additionally, the model considers that each region has a representative agent with endowments of four primary production factors: capital, labor, natural resources, and CO_2 certificates. The labor market is imperfect and heterogeneous, being divided into highly qualified (skilled) and less-qualified (unskilled) labor. Finally, the model is recursive-dynamic and uses Cobb–Douglas, Leontief, and constant elasticity of substitution (CES) to represent production and utility possibilities based on [132]. The electricity-generation system in the model has 18 production possibilities described as combinations of technology and load categories. Considering the sectoral disaggregation in TIMES PanEU and NEWAGE, the sectors in NEWAGE can reflect the development in all the energy service demands in TIMES. The framework of NEWAGE enables the analysis of the impacts of various political interventions on macro-economic indicators, such as GDP growth, sectoral gross value added (GVA), employment, competitiveness, and social welfare. Precisely, for the coupling procedure, regional net income, calculated as the sum of income from capital and labor minus payments of taxes to the government, and regional utility, defined as households' total consumption, are also calculated.

Before initiating the iteration process, NEWAGE and TIMES PanEU need to correspond to their socio-economic assumptions. Therefore, projections about population and GDP growth are assembled to a standard reference scenario, within the scope of this thesis to EU Reference Scenario [20], which is implemented in both models together, according to the proposed method in [135]. Additionally, NEWAGE is calibrated to the technology development of TIMES PanEU by replicating its sectoral CO_2 emissions and electricity mix of the chosen reference scenario. The harmonization and calibration processes are supposed to ensure comparability between the results from both models [114], which also confirms the linking process's transparency.

The iteration process begins with TIMES PanEU, as it produces the first results of the electricity generation mix. Following, NEWAGE is set for the designed scenario and fixes, with a slight deviation margin, its electricity generation mix to be at the same level with TIMES PanEU. Next, NEWAGE produces GDP development results, sectoral Gross Value Added (GVA), net income, and utility [114]. Finally, the existing sectoral energy service demands in TIMES PanEU are updated according to Equation 2-10 and the sectoral match between the models given in Table 1 and in [114]. As there are feedbacks between the models with the updated energy service demands in TIMES PanEU and the electricity mix in NEWAGE, the two models are run iteratively.

Although the relation between energy use and economic developments has already been proved in [136], it is also discussed in [51, 65, 137] that energy service demand values are not only affected by the economic developments in a country. There are factors such as population growth, efficiency improvements, energy production, and transportation of energy which also influence the energy service demand development. In [51], based on the findings for the relationship between economic growth and energy service demand in [138], a methodology was developed to quantify the correlation between the yearly change of demand segment and the yearly change in gross production in monetary terms of the particular sectors. The historical data was used to come up with such a correlation. Since the scope was limited to a single country and mainly to industrial sectors, it was conceivable to develop such a correlation in [51]. In this thesis's scope, the objective is to integrate the feedback for all the Member States in the EU and all the energy service demands in the energy system. A constant decoupling factor (*DF*) is applied to balance the impact of macro-economic variations and other impacts on the energy service demands, which also reveals a certain degree of demand inelasticity in energy services [114], to be consistent between different demands and the Member States:

$$ED_{s,(x+1)}^{SCE} = ED_{s}^{REF}\left(\frac{EV_{i,x}^{SCE}}{EV_{i}^{REF}}\right)(1-DF) + \; ED_{s}^{REF}DF \qquad \text{Eq.2-10}$$

Where;

ED: *energy service demands of sector s*

x: *iteration number*
SCE: *a particular decarbonization scenario*
REF: *the reference scenario.*
EV: *the level of the economic variable i, which is related to sector s according to Table 1.*

DF represents the decoupling factor, which determines the weight that the sectoral energy demands from the reference scenario will have on the updated values. Thus, if a decoupling factor of 25% is applied, it is assumed that the general economic development reflects 75% of the demand development. In comparison, 25% are mainly influenced by other factors, such as efficiency gains, changing consumption patterns, or population. Developing such a correlation to quantify how much energy service demands are solely influenced by economic development or on how big of a role other socio-economic parameters and developments play is not part of the scope of this thesis due to energy-service demand disaggregation and variety of the countries, a sensitivity analysis is conducted, and three different decoupling factors applied for the link between TIMES PanEU and NEWAGE - 25 %, 50 %, and 75 % - and the iteration process is carried out between the models with these different decoupling factors.

To summarize, the steps of the iteration process are the following:

1. TIMES PanEU provides the electricity mix results calculated for a decarbonization scenario to NEWAGE, as shown in Figure 3.
2. NEWAGE calculates economic variables influencing energy service demand growth patterns based on the provided results by TIMES PanEU.
3. Energy service demand projections are updated in TIMES PanEU based on chosen economic variables as calculated by NEWAGE based on technology match given in Table 1.
4. The convergence criterion is computed.
5. If the convergence criterion is not within the convergence range, go back to step 1.

During the coupling process, the relative variation of GDP from NEWAGE between the iterations as the convergence criteria is chosen. This choice is based on the fact that GDP is a product of all production sectors and consumption, so it stops varying when other economic variables in NEWAGE reach convergence. A derivation of ± 0.005% is assumed to be sufficiently small to account for convergence. The iteration process is carried out with TIMES PanEU, in which damage costs are already considered as part of the optimization to complete the integrated assessment framework.

2.5 Identification of Key Mitigation Options

To identify the critical mitigation options during the transition by considering the feedback loops from the economy and environment based on the integrated assessment framework as explained in Section 2.4., three pathways are developed to examine the various decarbonization paths' potential dynamics for the energy transition as relevant to the second research objective in Section 1.2. Therefore, three different trends are concentrated by focusing on the different technology mixes for a potential transition [109]:

- Coalitions for a Low-carbon future (CL): energy carrier suppliers take on the highest burden in the decarbonization of the EU energy system, while consumers observe it mostly passively or respond to policies as they come.
- Local Solutions (LS): consumers (especially households) engage in the transition towards a low-carbon energy system by choices on end-use appliances, energy efficiency measures, and transportation technologies.
- Paris Agreement (PA): the EU undertakes an ambitious decarbonization effort, with a target of 95% reduction of CO_2 emissions by 2050. This overshoots the Paris Agreement pledges and is more in line with the discussed carbon neutrality. Both energy carrier suppliers and consumers engage in the challenge.

Table 2: Summary of key modeling assumptions of the pathways [139]

	Coalitions for a Low carbon path (CL)	***Local Solutions (LS)***	***Paris Agreement (PA)***
Policy	*83% decarbonization target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels;* *Ambitions on non-ETS sectors different by clusters of Member States;*	*83% decarbonization target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels;* *Ambitions on non-ETS sectors different by clusters of Member States;*	*95% decarbonization target across all sectors in the EU as a whole by 2050, compared to 2005 levels*
Environment	*Changes in heating and cooling degree days computed assuming RCP4.5*	*Changes in heating and cooling degree days computed assuming RCP4.5*	*Changes in heating and cooling degree days computed assuming RCP2.6*
Technology	***Significant penetration of centralized renewable energy supply options*** *Limited penetration of solar heat pumps and renovation rate of buildings in the residential sector;* *Breakthrough of floating platforms for offshore wind*	***Uptake of low carbon technologies in households and road transport*** *Limited penetration of nuclear and CCS;* *Breakthrough of Building-Integrated PV;*	***General strong recognition of the impacts of climate change*** *Breakthrough of Building Integrated PV;* *Breakthrough of floating for offshore wind* *Availability of CCS, including BECSS*

Sector Specific Assumptions	*Higher push to decarbonization of industrial processes-sector specific CO_2 reduction target is defined;*	*Higher decarbonization of transportation and residential sectors-sector specific CO_2 reduction targets are defined;*	

This assessment aims to compare those pathways' implications considering the cause-effect relationships between sectors to a low carbon society on the energy system to identify the critical mitigation options. According to the trends above, the narratives' critical features for each pathway and the main relative assumptions are translated into modeling assumptions and summarized in Table 1 and Table 2. Elaborated information about the pathway assumptions and their development can be found in [109].

Table 3: Sectoral specific reduction targets of the pathways [139]

Pathway		**CL**	**LS**		**PA**
Sectors		Industry	Residential	Transport	N.A.
Milestone Targets CO_2 Emissions	**2030**	750 Mt	233 Mt	446 Mt	
	2050	295 Mt	60 Mt	80 Mt	

2.6 Assessment of Critical Uncertainties in the Energy System

The techno-economic assumptions of the technologies are mostly exogenously defined in the energy systems [3]. Therefore, they need to be verified to define the mitigation technologies' role during the energy transition, as stated as part of the second research objective in Section 1.2.

Learning curves have been developed in the literature to project the future cost of the technologies. According to the learning curve approach, the specific investment cost is a function of cumulative capacity or cumulative production at the global level [140]. Although the methodologies such as the endogenous implementation of learning curves have been developed [34] to internalize the mitigation technologies' cost assumptions, there are limitations with this approach. As the learning curves are a global phenomenon, global deployments are required for an accurate implementation [140]. Another limitation appears with the learning rates' uncertainty [27, 33, 34, 35]. The learning rates of the technologies are determined based on the historical progress of a technology [35] which might also change over time when the technology progresses faster than expected; this would mean that the cost assumptions can also change over time for the technology. Therefore, the uncertainty assessment is essential to address such vagueness with the input assumptions in the energy system models. The uncertainty is also applied with the available potential of the mitigation technologies. Although sun and wind are unlimited, the sources such as biomass require attention in terms of the sustainable potential to be counted as renewable. Uncertainty assessment is integrated into this thesis's scope to verify the mitigation technologies' role through the energy transition and develop short-term hedging strategies, considering uncertain aspects of the energy transition.

Sensitivity analysis is a standard method in energy system analysis to support the policy decisions related to uncertainties [141]. There are additional approaches developed to address the uncertainties in the energy systems, as discussed in Section 1.3.2. with the applications in the contemporary research. According to the systematic review carried out in [75], mainly four approaches have been applied so far in energy system models additional to sensitivity analyses: Monte Carlo analysis, stochastic programming, robust optimization, and modeling to generate alternatives. [142] differentiates the uncertainties studied in the energy systems as parametric and structural. While parametric uncertainties refer to the values for the input assumptions given to the model due to lack of knowledge, structural uncertainties are defined as the ones in the model equations. Based on these definitions, the uncertainties we want to study in this paper are classified as parametric uncertainties. As stated in [75], parametric uncertainties cannot be addressed with the modeling to generate alternatives approach. Between the other methods, a reliable probability distribution is required for the uncertain parameters for the Monte Carlo analysis. Additionally, high numbers of scenarios are necessary, increasing the computational time for the analysis, which is primarily an issue when dealing with already complex and computationally intensive models, such as Pan-European energy system models. As it is not possible to overcome the burden of computational time, Monte Carlo analysis is also not applicable for this study. The alternative approach of robust optimization does not require probability distributions. However, it also does not provide a unified hedging strategy [75]. Here, hedging strategy refers to the near-term (stochastic) modeling results up to the point of uncertainty resolution, i.e., it describes the optimal strategy to minimize possible adverse impacts from uncertain future developments. In contrast, results after resolving the uncertainty are referred to as recourse strategies. Stochastic programming can be introduced in energy system models to derive a single hedging and possible recourse strategies for a limited, small number of considered uncertainty. Since the near-term hedging strategy is also in the interest of this thesis, the stochastic programming approach is opted to analyze uncertainties with the deterministic sensitivity analyses since the deterministic sensitivity analysis is identified as a standard method to deal with the uncertainties [143]. Additionally, stochastic programming enables quantifying and analyzing the related costs of the uncertainties and comparing them with the deterministic results as a result of sensitivity analyses [116].

2.6.1 Stochastic Programming with TIMES

Stochastic programming can be applied in the TIMES model generator. For the application, building up a stochastic tree and the activation of the relevant function are the first steps. In a deterministic model version of the energy system models, the uncertainties' impact can be identified with sensitivity analysis. According to a given scenario tree and given probabilities, stochastic bottom-up energy system models optimize the discounted system cost of future State of the Worlds (SOW) based on the weighted average of the given probabilities for each SOW [71]. The model takes into account the uncertainties assigned by the different distributions, which can be defined for the selected input parameters instead of single deterministic values for these input parameters [116].

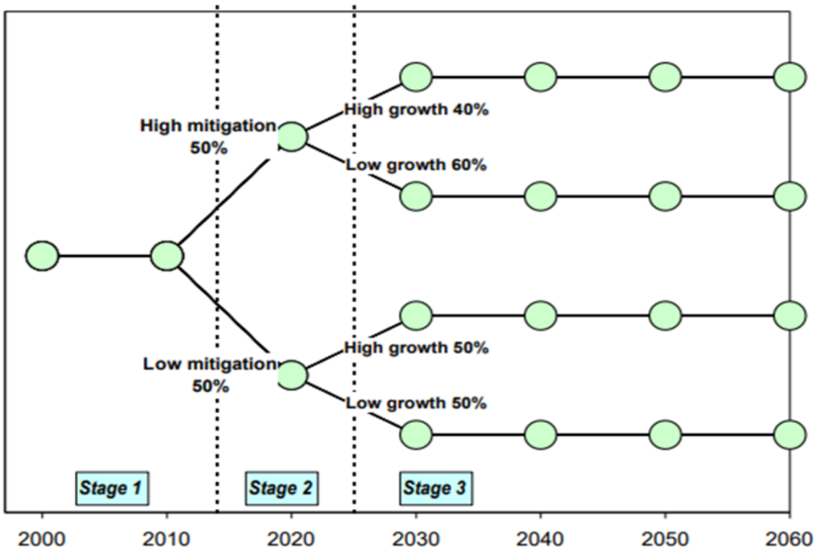

Figure 4: Event Tree for a three-stage stochastic TIMES Example [144]

Stochastic programming in TIMES model generator is structured according to a stochastic scenario tree. The stochastic scenario tree defines the random variables for the selected uncertain input parameters instead of having a single value in a typical deterministic run. An example of a stochastic scenario tree is given in Figure 4. For each SOW, the probability is determined as an exogenous parameter. This probability determines the likelihood of the uncertainty to occur. According to the given probability and specific assumptions defined based on the assigned uncertainty and on a SOW, the model calculates the optimized hedging strategy and recourse strategies, considering the expected cost of the system's uncertainty [116]. The hedging strategy in Figure 4 refers to Stage 1 before the uncertainties are resolved. Stage 2 and 3 are defined as recourse periods.

The stochastic model relaxes the assumption of perfect foresight. It does distribute the time horizon into a single near-term hedging strategy and multiple recourse periods. However, only a single solution is computed based on a single variable by a deterministic model. The objective function of the stochastic model is determined as below in Equation 2-11 [116]:

Minimize:

$$\sum (w \in W(t)) \sum_{t \in T} C\,(t,w)\, X(t,w)\, P(t,w) \qquad \text{Eq. 2-11}$$

Where:

w	*the SOW*
t	*time period*
W(t)	*the set of SOWs for time period t*
T	*set of all time periods*
C (t,w)	*the row vector in time period t under SOW w*
X(t,w)	*the column vector of decision variables in period t, under scenario w, C (t,w)*
P(t,w)	*probability of the scenario w in period t*

and;

$$\sum_{w \in W(t)} P\,(t,w) = 1 \qquad \text{Eq. 2-12}$$

According to the optimization function and optimized hedging strategy, TIMES calculates the set of results according to the total numbers of the SOWs in the last stage based on the given probability and one objective function, which considers the cost of uncertainty for the random variables [144]. The stochastic tree in Figure 4 gives four sets of results (recourse strategies) as four SOWs defined in the last stage. According to the scenario tree, one or more specific assumptions according to relevant uncertainty can also be defined.

2.6.2 Building up the Stochastic Scenario Trees

Based on the feedbacks from [109, 114], uncertainties for the transport sector around EV learnings, biomass availability, and having various GHG reduction targets in the energy system are identified to be further assessed in addition to the traditional sensitivity analysis with stochastic programming to verify the role of EVs and biofuel vehicles during the energy transition in the EU.

Different studies have come up with different learnings and cost projections for the large-scale lithium-ion batteries and battery packs in EVs [27, 145]. Since TIMES PanEU covers only the European regions, the cost assumptions based on global learning are given exogenously. In [27], five different product price curves are developed according to the S curve approach for the deployment and learning rates for the battery packs in EVs based on the learning curve principle. Historical product prices and cumulative installed capacities based on peer-reviewed literature are used to derive the learning rates in [27]. The learning rates calculated are in the 16% ± 4 intervals. The middle learning scenarios did not result in any significant differences compared to existing assumptions in the deterministic TIMES PanEU version so, they were not applied as a part of the uncertainty assessment.

The highest and lowest reduction curves of battery packs presented in [27] are incorporated in our study to determine the EVs' cost paths. As different cost curves are available in [27], to be consistent for the source of the information and reliable comparability for high and low learning scenarios, only those numbers are applied for the analyses. These battery packs' cost figures are incorporated into the vehicles' existing cost figures in TIMES PanEU, based on [146] to reflect the technology's cost reduction. Different learning rates and cost of battery packs bring the 13% cost difference for the battery electric vehicles starting from 2030. This difference is relatively lower for the plug-in hybrids, which is around 2% due to the share of the batteries’ cost. The uncertainty range is also similar to the battery EVs for the electric trucks and buses, around 12%, but this interval is moderately small for hybrid technologies, 2%. Detailed cost assumptions used for battery costs and the electric vehicles in high learning and low learning scenarios as part of this thesis are given in [116].

Biomass and the fuels sourced from biomass are anticipated as mitigation options in many parts of the energy system [147]. With the development of new technologies such as biomass CCS, concerns are also raised concerning the source's availability for non-CCS applications [68]. According to TIMES PanEU results based on several scenarios with different reduction targets [109] also as part of this thesis, the share of biomass in 2020 in the final energy consumption of transport is calculated around 10%. In the low biomass availability scenario to be studied in the uncertainty assessment, the maximum share of biofuels is kept at 2020 levels as calculated in the scenarios mentioned in [109], representing a lower bound in development regarding the given renewable targets for 2020 [148]. Based on previous model results considering the total final energy consumption of transport in 2050 [109], it is defined that the absolute amount of biofuels in EU28 should not exceed 1500 PJ as the maximum potential in 2050 for the low biomass potential availability in the transport sector. The biomass bounds calculation is given in [116]. A specific bound is not defined for the biomass usage in the transport sector in high biomass potential availability. Therefore, the uncertainty range in terms of biomass availability is enormous as only the bound for the low biomass potential is determined in the transport sector. However, according to regions explained in Section 2.3, a total potential for biomass availability concerning the entire energy system is still considered in both cases [148].

Table 4: Uncertainty model runs [116]

2050 GHG Reduction Target	Learning in EVs	Biomass Potential
80% according to the level in 1990	High Learning (HL)	High Biomass (HB)
	High Learning (HL)	Low Biomass (LB)
	Low Learning (LL)	High Biomass (HB)
	Low Learning (LL)	Low Biomass (LB)
90% according to the level in 1990	High Learning (HL)	High Biomass (HB)
	High Learning (HL)	Low Biomass (LB)
	Low Learning (LL)	High Biomass (HB)
	Low Learning (LL)	Low Biomass (LB)

After determining the input parameters with the absolute numbers, the stochastic trees are structured to assess the identified uncertainties with 4 SOWs. The stochastic trees built in this thesis by combining the considered uncertainties are given in Table 4. During the construction of the stochastic trees, the computational time is also taken into account by keeping the number of the SOWs limited but including relevant assumptions.

Scenario Tree - Short hedging [116]

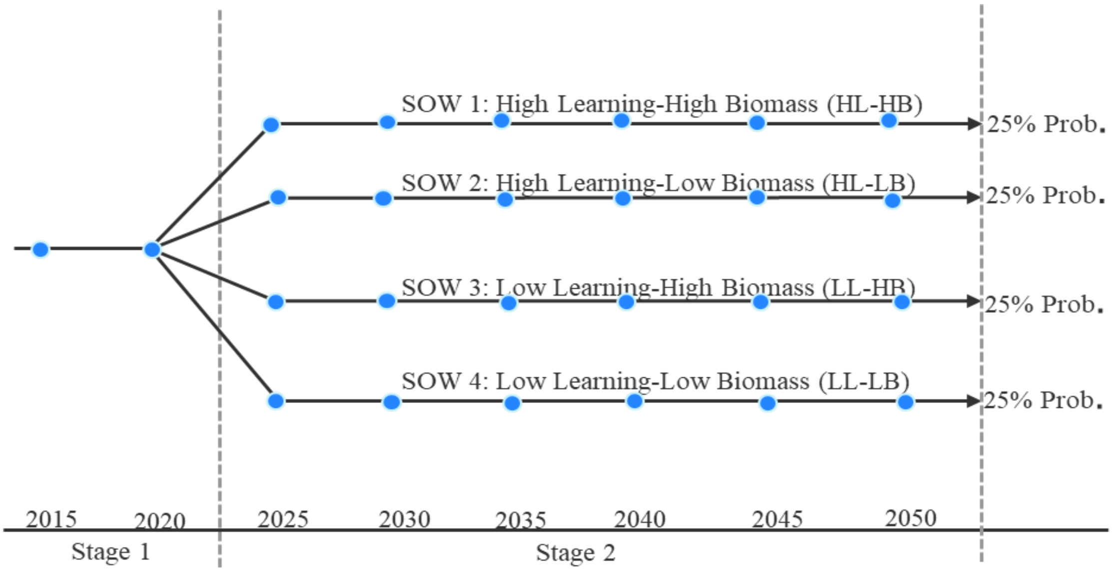

Figure 5: Stochastic scenario tree – Short hedging [116]

Since the aim is to study the impact of learning uncertainty for battery packs in EVs and the uncertainty of biomass availability by going beyond sensitivity analysis to gain insights, these two factors determine the SOWs in the stochastic tree according to the methodology. As the current version of the stochastic programming implementation in TIMES is based on directly solving the equivalent deterministic problem as explained in Section 2.6.1, the scenario variations are applied in Table 4 to build the stochastic scenario tree. According to the assumptions explained above, the EV costs and biomass potential are also expected to vary after 2025. Therefore, the stochastic tree's second stage is assumed to be commenced after 2025 according to the same assumptions in [27]. Based on this, a two-stage stochastic tree with four SOWs is developed and implemented with TIMES PanEU. The highest and lowest learning scenarios in [27] are applied in our study for battery packs in EVs. Low biomass and high biomass availability scenarios are further integrated into the scenario tree. Biomass availability and the learning scenarios are combined as schemed in Figure 5. Equal probabilities are given to each SOW due to a lack of information regarding the likelihood of possible development. However, considering the consistency between the low and high learning assumptions in [27] and the probability of being occurred cannot be so different, which means that each of the four SOWs has a 25% chance of occurring. This approach has already been applied in different studies [71, 149].

Scenario Tree - Longer hedging [116]

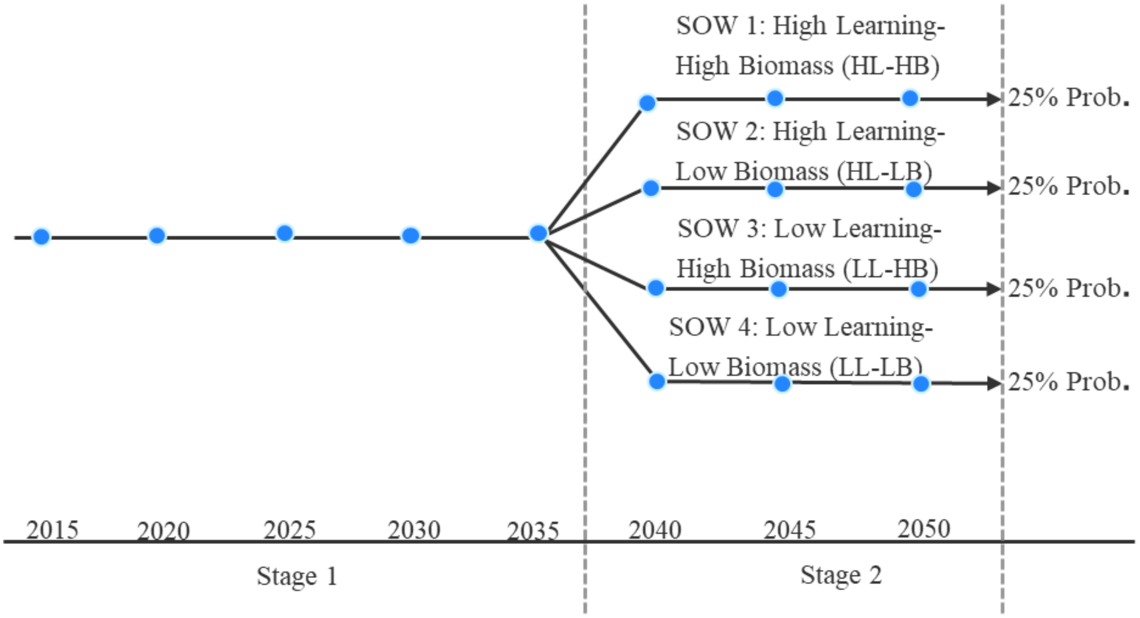

Figure 6: Stochastic tree – a variation of hedging period with 80% reduction target [116]

Since it is also uncertain when the given uncertainties are resolved, a sensitivity analysis to investigate the impacts of having a longer hedging period for the considered uncertainties is designed. As the aim is to have a longer hedging period, the beginning of the 2nd stage is shifted to 2040 instead of 2025. Therefore, the stochastic scenario tree in Figure 5 is restructured, as shown in Figure 6. Biomass bound in transport is kept constant at 1500 PJ in all the SOWs until 2040. In High Biomass (HB) SOWs, this bound is relaxed afterward, but the energy system's overall biomass potential is still taken into account. The learning regarding EVs is also kept constant until 2040, after which a substantial reduction in the battery packs is assumed in High Learning (HL) SOWs. The EV assumptions for this scenario tree are also given detailed in [116]. Equal probability for each SOW, 25% probability, is defined.

Scenario Tree - Combining reduction target and biomass uncertainties [116]

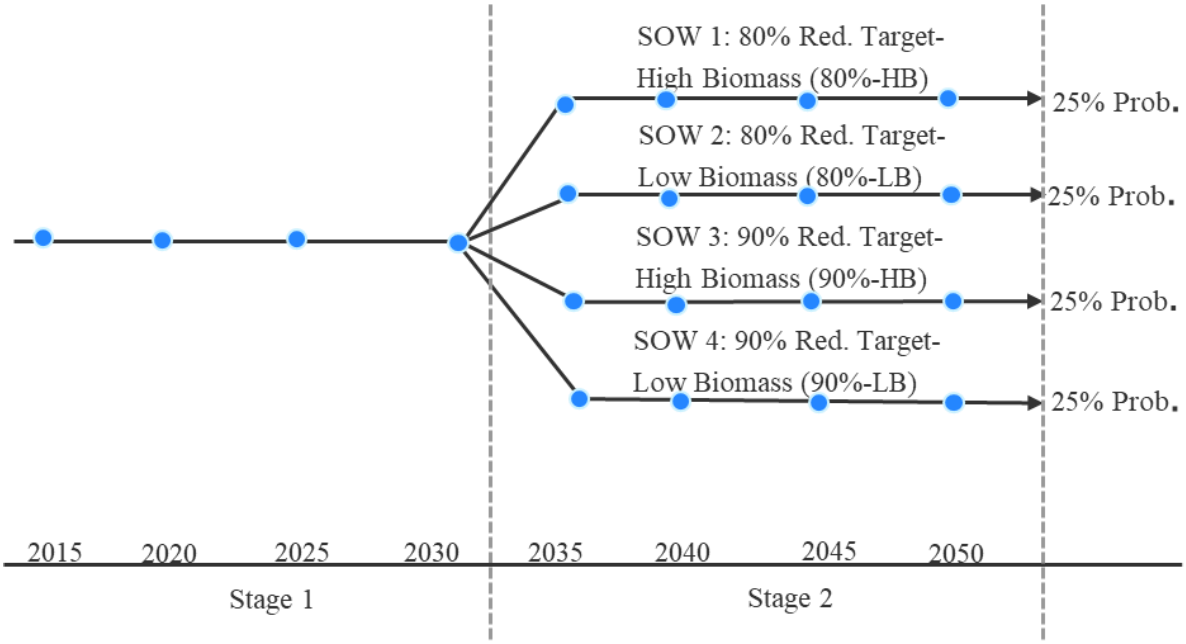

Figure 7: Stochastic scenario tree – combining reduction target and biomass uncertainties [116]

The stochastic tree is restructured as part of the assessment to bring together the policy uncertainty considering the entire energy system and biomass uncertainty in the transport sector. These two uncertainties are combined, policy uncertainty with having different decarbonization targets and biomass availability, to study the transport sector's design by considering the feedback from and to the other sectors in the energy system. According to currently discussed targets concerning the Green Deal [11], the emission reduction path aims to achieve a 50% GHG reduction in 2030 based on 1990 levels. Based on this assumption, the uncertainty associated with the GHG reduction target will resolve in 2035. In light of this information, the scenario tree is restructured as given in Figure 7 by initiating the 2nd stage in 2035. Until the 2nd stage, biomass bound again is kept constant as 1500 PJ across all the SOWs in the transport sector. After 2030, the reduction target milestones in 2040 are implemented as described in Section 3 with an 80% Reduction Target SOW and 90% Reduction Target SOW. Equal probabilities are assigned for each SOW. For the EVs, high learning assumptions are incorporated across the SOWs [116].

3 Publications

3.1 Publication I

On the Way to a Sustainable European Energy System: Setting up an Integrated Assessment Toolbox with TIMES PanEU as the Key Component

Authors: Pinar Korkmaz, Roland Cunha Montenegro, Dorothea Schmid, Markus Blesl, Ulrich Fahl

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Author's contributions: Pinar Korkmaz, Roland Cunha Montenegro and Ulrich Fahl developed the initial concept for the analysis together**.** Pinar Korkmaz further improved existing TIMES PanEU model by linking EcoSense and NEWAGE and identified the findings. Additionally, she carried out the decomposition analysis to investigate the role of different mitigation options as well as drivers of decarbonization in the energy system. In addition to the relevant parts of the manuscript, Introduction and Discussion sections were written by her. The NEWAGE part of the study was delivered by Roland Cunha Montenegro and the EcoSense part by Dorothea Schmid. They also contributed to the Introduction and Discussion. Ulrich Fahl and Markus Blesl reviewed the manuscripts and provided the comments for the final structure.

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On the Way to a Sustainable European Energy System: Setting Up an Integrated Assessment Toolbox with TIMES PanEU as the Key Component

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Abstract: The required decarbonization of the energy system is a complex task, with ambitious targets under the Paris Agreement, and related policy analysis should consider possible impacts on the economy and society. By coupling the energy system model TIMES PanEU with the impact assessment model EcoSense and the computable general equilibrium model NEWAGE, we present an integrated assessment toolbox for the European energy system capable of internalizing health damage costs of air pollution while simultaneously accounting for demand changes in energy services caused by economic feedback loops. The effects of each coupling step are investigated in a scenario analysis. Additionally, CO_2 decomposition analysis is applied to identify the main drivers to decarbonize the energy system. Our results show that integrating externalities forces the system to take early action, which provides benefits on the societal level. Including macro-economic variables has a negative effect on energy service demands and generally reduces the need for structural change, which are still the main drivers of decarbonization. The tighter the models are coupled, the fewer the iterations needed and the lower the CO_2 prices resulting from the carbon cap and trade system. In this aspect, an integrated view can provide valuable insights to determine efficient and effective decarbonization paths.

Keywords: integrated assessment model; Pan-European model; energy system transformation; sustainable European energy system; CO_2 decomposition analysis; general equilibrium model

1. Introduction

1.1. Motivation

In order to meet the Paris Agreement targets and limit global warming accordingly, the European Union (EU) must reduce its greenhouse gas (GHG) emissions by at least 80% in 2050 compared to 1990 levels or even achieve carbon-neutrality as also outlined in its “Clean Planet for All” strategy [1]. The required energy transition, which implies deep fuel shifts and significant investments in new technologies, is likely to have impacts on economies since economic growth and energy supply are closely linked, usually resulting in an increased per capita energy and carbon intensity [2]. Depending on the chosen path, the EU energy transition will also affect society and the environment in different ways. Similarly, societal decisions in other policy areas, especially when dealing with other environmental issues than climate change mitigation, may affect the EU energy transition. As, for example, both climate change mitigation and air pollution control require changes in the energy system, they may hamper or foster each other to achieve their goals [3].

Therefore, the EU energy transition should be analyzed by also taking into account different dimensions such as the economy and the environment which also affect the decision-making processes in the energy system. To this end, different integrated assessment models (IAM), for both EU and non-EU regions, have been developed and applied in recent years to analyze different transition pathways, identify relevant decarbonization drivers and understand their impacts on the energy system as well as possible effects on the economy and society. Before introducing the Integrated Assessment Toolbox developed and applied in this study, a review of previous work in this field is presented first.

1.2. Background

The need for an integrated assessment framework to study energy transitions has been widely recognized in recent literature. Integrated assessment models or frameworks combine expertise from different disciplines and are often applied to identify, study and assess climate change impacts, key challenges and respective mitigation strategies (A good overview of Integrated Assessment Frameworks in the field of climate change mitigation is given in a "Carbon Brief" Q and A: https://www.carbonbrief.org/qa-how-integrated-assessment-models-are-used-to-study-climate-change (last checked: 15-12-2019)). Their main purpose is to provide insights into how, based on constructed scenarios, human behavior, development and societal choices affect different systems and the natural world. In particular, integrated assessment models are also applied in the Intergovernmental Panel for Climate Change (IPCC)assessment reports to identify and discuss possible impacts on and interactions between economic and social developments, technical system and natural environments of different emission scenarios. In these world-wide studies, six different integrated assessment models are applied, covering different spatial areas, representing different modelling approaches and partially focusing on different aspects [4]. In this review, we focus on other integrated assessment models applied outside the IPCC studies, which have an energy system model at their core.

The link between an energy system model and macroeconomic model, for example, has been established in the MESSAGE-MACRO model [5]. The corresponding study focused on the factors which affect the energy supply costs calculated in the energy system model by feeding these costs to the macroeconomic model to create consistency between the energy demand and supply curves. For two different scenarios, the gross domestic product (GDP), energy supply and demand, and energy prices were compared after the link was established.

In another study, the techno-economic TIAM-WORLD model has been linked with the general equilibrium model GEMINI-E3 together with a climate model, PLASIM-ENTS, to specifically discuss the impacts of climate change on the energy system with an emphasis on heating and cooling demand [6]. The results of this study showed that the link between these three models shows a different picture in terms of required investments in generation capacity at the regional level than the energy system model on its own. This, in turn, results in increased energy prices, especially due to rising cooling demand because of increasing average temperatures. It is observed that the welfare gains and losses are affected by changes in energy exports and imports. However, the changes in the heating and cooling demands do not have a significant impact on economic parameters such as GDP.

Studies with links between energy system and impact assessment models can be found in literature as well. In [7], the methodology to internalize life-cycle data and external costs in a TIMES model is presented. According to this link, the unit health damage costs caused by the pollutants are calculated exogenously and they are fed back to the energy system model. The synergy between the environmental taxes on pollutants and different CO_2 mitigation scenarios in Italy are discussed in detail in [8]. Similar analyses are also delivered at the EU level to see the impact of externalities in the energy system [3]. Their results indicate that internalizing the externalities in a decarbonized energy system induces welfare savings by further reducing air pollution. The energy system is still able to achieve the given

GHG reduction targets with lower utilization of biomass and conventional carbon capture and storage (CCS) technologies due to associated health impacts.

Aside from integrated assessment models, CO_2 decomposition analysis is usually applied in different parts of the energy system to identify the main drivers for decarbonization and their impact on the energy transition, including economic effects reflected in activity and demand changes. In [9], a methodology has been proposed to generate marginal abatement cost curves based on the results from an energy system model and a decomposition analysis of CO_2 reductions. Four categories represent the relevant effects in emission reductions: demand changes (activity effect), technology switches (structure effect), efficiency improvements (fuel intensity effect), and reduction in the carbon intensity of secondary energy carriers (carbon intensity effect). For the decomposition analysis, the log mean divisia index (LMDI) has been chosen as the preferred method. In the study the focus was on the transport sector decarbonization in the UK and, according to their findings, structural shifts and reduced carbon intensity of fuels are responsible for the majority of emission reductions. On the other hand, demand reduction, which is assessed by considering elastic demand functions in the model, shows only a minor but constant contribution to CO_2 reductions in transport. In another study, the relative effects of different factors on the changes in CO_2 emissions have been analyzed for the Turkish manufacturing industry between 1995–2001 [10]. Again, LMDI has been applied as a decomposition method with energy intensity and economic activity being identified as the main drivers. LMDI was also used in [11], with a focus on the Iranian energy market between 2003–2014. Industrial energy consumption, the carbon intensity of electricity generation and carbon emission due to total (fossil) fuel consumption, are investigated as drivers. They concluded that increased consumption was the main reason for increases in Iran's CO_2 emissions.

1.3. Research Question

According to the available literature and based on our best knowledge, so far, an energy system model is either linked to an environmental impact assessment or a macro-economic model and only impacts from a single link are discussed. Consequently, as we aim to fill this gap, the integrated assessment toolbox developed in this research brings all of these three elements together and considers the technical, economic and environmental dimensions simultaneously in the energy transition analysis on the EU level. Through a comparative and qualitative scenario analysis, the toolbox aims to provide new policy insights regarding economic impacts of decarbonization, their relation with and effect on the energy system as well as potential trade-offs between energy system transitions and related externalities. This study introduces an additional novelty by applying a CO_2 decomposition analysis to assess the impact that each model coupling has on the decarbonization path.

2. Methods

In this section, the models applied in the study are introduced first. Next, the methodology for the links between the models is described and the process to create the Integrated Assessment Toolbox is presented. In the following sections, we present a methodology to assess the impacts of linking the models on the CO_2 decomposition, as this is one of the aims of the study. Finally, the section is concluded with the description of the scenarios applied to identify the impacts of the links in the EU energy transition.

2.1. Models Applied

In this section, we introduce the three models applied in our study—TIMES PanEU, EcoSense and NEWAGE—which provide the foundation for the Integrated Assessment Toolbox as depicted in Figure 1.

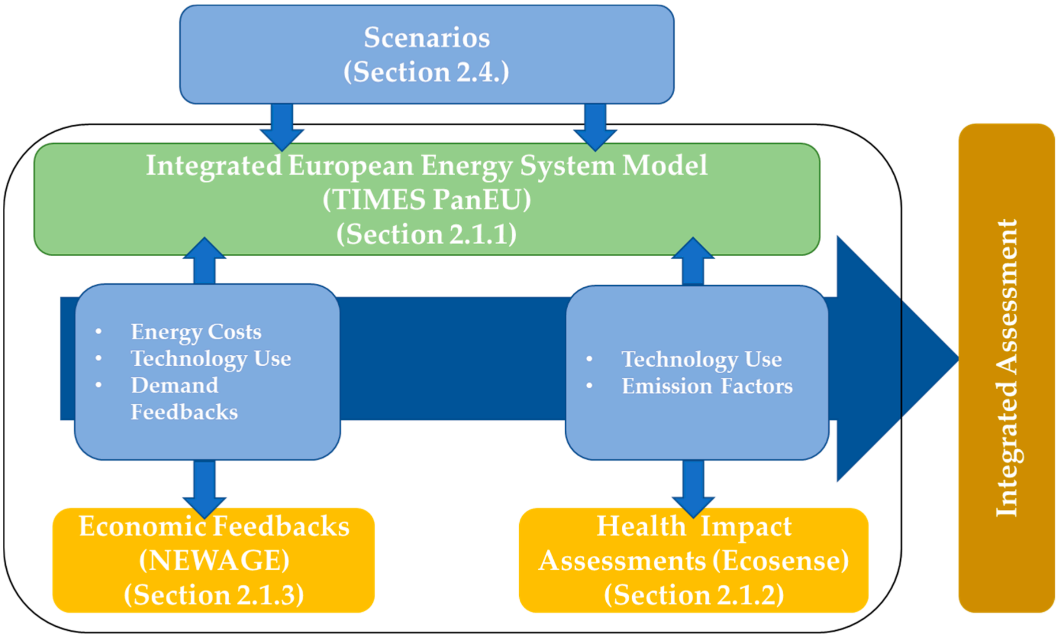

Figure 1. The Integrated Assessment Toolbox.

As an energy system model, TIMES PanEU is employed. The model generator TIMES has already been employed in multiple studies proving its compatibility to provide similar analyses, as shown for example in [12,13]. In particular, TIMES PanEU also fulfills the most relevant requirements such as sectoral integration, covering the entire energy system as well as the potential of the domestic sources such as biomass. As it also includes all the member states, it can also provide policy-relevant insights not only at the EU level but also at the national level. EcoSense is chosen as a health impact assessment model in our study. EcoSense is a reference implementation of the Extern-E methodology, which forms the foundation of externality assessment in the field of energy. As such, EcoSense is considered to be best fitting for the Integrated Assessment Toolbox. NEWAGE is applied as a general equilibrium to have the macro-economic insights through the energy transition. NEWAGE has a detailed electricity sector modeled which is quite crucial in areas such as a coupling process. Additionally, considering the sectoral disaggregation in TIMES PanEU and NEWAGE, the sectors in NEWAGE can reflect the development in all the end-user sectors in TIMES PanEU.

2.1.1. Energy System Model: TIMES PanEU

TIMES PanEU is employed as an energy system optimization model to be further linked to EcoSense and NEWAGE in our study.

TIMES PanEU is built with the TIMES model generator, in the modelling environment GAMS. It is a model generator to create bottom-up energy system models with linear programming. It has been developed and maintained within the Energy Technology System Analyses Program (ETSAP) by the International Energy Agency (IEA) [14]. The data management system (VEDA-TIMES) creates an energy system model [15]. Through this data system, the input data, the structure of the model and all the scenario-related information are given to the model and they are converted to mathematical equations. The model aims to minimize the total discounted system cost in a given timeframe to meet exogenously given service demands [16] with a perfect foresight principle. TIMES PanEU covers the European Union countries as well as Norway and Switzerland and each country represents a single region in the model. The modelling horizon spans from 2010 to 2050, split into 5 year-time steps. A year is divided into 12 time-slices, 4-seasonal and 3-day levels (day, peak and night). Greenhouse gas emissions (CO_2, CH_4, N_2O) and other pollutants (SO_2, NO_x, CO, NMVOC, $PM_{2.5}$, PM_{10}) are included in the model. The basic structure of the model is called reference energy system (RES). RES includes all relevant energy, material, and emission flows from the primary production to meet the demand of energy services for each region defined in the model [17]. RES of the model covers the entire energy system, from the supply of resources to the service demand. Different technologies are modelled to make the interactions possible between the parts of the energy system. Primary energy sources are modelled according to country potentials and the trade possibilities from the neighboring countries. Different cost potential curves are defined for each of the sources such as crude oil, natural gas, coal, lignite, etc. The World Energy Outlook 2016 prices [18] and average country mining costs are taken as a reference to determine the cost figures. Various bioenergy carriers are included by taking into account the country's potential and their costs. No constraints are considered for biomass trade within the EU regions. Land availability for biomass cultivation is given in the model based on [19]. Additionally, other conversion technologies such as refineries, gasification and power-to-gas are part of the model [14].

In the electricity sector, the electricity supply at different voltage levels is modelled through different technologies. The technologies are classified according to the input fuels and technology type and they are aggregated by power plant type. New technologies such as electricity storage, hydrogen technologies and CCS technologies are modelled as investment options during the time horizon. The availability of certain technologies such as CCS is determined according to the expected schedule of technologies to be commercially available in the market [20]. Cogeneration plants (CHP) for centrally supplied district heating are given as a choice in the model to provide both electricity and heat. Power-to-heat technologies together with heat storages are applied in the public heat supply. Capacities deployed, generations, energy prices, energy flows as well as emissions are calculated based on given input parameters to the model.

The industrial sector is divided into energy-intensive and non energy-intensive industries. The energy-intensive industries cover the categories iron and steel, aluminum, copper, ammonia, chlorine, cement, lime, flat glass, and paper; whereas the non energy-intensive industries include other non-ferrous metals, other chemicals, other non-metallic minerals, food and tobacco and other industries. Industrial auto producers are also modelled [21].

In the household, commercial and agriculture segment, the energy service demands are disaggregated according to different sectors. Various technologies, aggregated according to technology type and energy carrier, are implemented to provide the energy service demands. The process to supply the agriculture demand is defined as one general process. The underlying assumptions of the existing demand figures in TIMES PanEU are consistent with the socio-demographic assumptions of the EU reference scenario [22].

The transport sector is disaggregated according to transportation mode: car, bus, motorcycle, passenger train, freight, air traffic (external and internal) and navigation categories. The passenger transport is modelled in the unit of passenger-km (Pkm). The freight is modelled in ton-km (Tkm). Different vehicles technologies based on the different energy carriers are modelled for each demand category mentioned above. Hybrid technologies are available. Technologies deployed together with the emissions that they produce and the energy flows are calculated in this sector as well. Mitigation options are also modelled to decarbonize the aviation and navigation sectors according to given milestones for the technologies in [23].

2.1.2. Health Impact Assessment Model: EcoSense

The impact assessment model EcoSense is applied to simulate and estimate health impacts due to air pollution across Europe. By following the impact pathway approach, as developed in the ExternE project series [24], EcoSense is designed to provide cost-benefit analysis of different air pollution mitigation scenarios up until 2050.

The impact pathway approach, as implemented in EcoSense, links changes in national emissions of the main air pollutants (SO_2, NO_X, NMVOC, NH_3, PM_{10} and $PM_{2.5}$) to health impacts across Europe. For this purpose, an atmospheric dispersion model is integrated with epidemiological studies and an economic assessment of impacts [25,26]. In a first step, a parameterized version of the EMEP/MSC-W model [27,28] is applied to estimates changes in concentration levels of Ozone, NO_2 and particulate matter ($PM_{2.5}$ and PM_{10}, incl. primary and secondary particles) attributable to changes in national emissions on a $0.5° \times 0.25°$ grid covering Europe and neighboring regions in Africa and Asia. Based on concentration-response functions recommended by the World Health Organization (WHO) [29], stating the change in relative risk of a specific outcome (inter alia increased mortality, hospital admissions and workdays lost) due to an increase in exposure to air pollution, additional cases related to the original changes in emissions are then estimated by also considering detailed population data and background disease rates [30]. The population data in EcoSense considers the spatial distribution of the high-resolution population density grid for Europe [31] as well as country-specific age structures and population projections based on UN data. Finally, the different health impacts are aggregated in monetary values by applying a willingness-to-pay approach for impacts on mortality ("Value of Life Year") and standard prices for all other impacts. EcoSense applies monetary values based on the HEIMTSA/INTARESE case study [26] with gaps filled by considering values from [30]. By relating the absolute costs of an emission scenario to the respective amount of emissions, unit cost factors can also be estimated. This application is described in more detail in [3] and [32].

2.1.3. General Equilibrium Model: NEWAGE

In this work we utilize the global computable general equilibrium (CGE)model NEWAGE (National European World Applied General Equilibrium, for more details about the NEWAGE model, visit https://www.ier.uni-stuttgart.de/forschung/modelle/NEWAGE/), to identify policy impacts in the economy. In this model, the world is divided into 18 regions, as shown in Figure A1, and production is split into 18 sectors, listed in Table A1. Additionally, the model considers that each region has a representative agent with endowments of four primary factors of production, namely capital, labor, natural resources and CO_2 certificates. Labor market is imperfect and heterogeneous, being divided into highly qualified (skilled) and less-qualified (unskilled) labor. Finally, the model is recursive-dynamic and uses Cobb–Douglas, Leontief and constant elasticity of substitution (CES) to represent production and utility possibilities, as shown in Figure A2, and are based on [33] and [34].

NEWAGE also has a detailed representation of the electricity-generation system, with 18 production possibilities described as combinations of technology and load categories, namely base, mid and peak, as shown in Figure A3. In this case, some technologies are considered to be used in every load category, such as gas, while others are used in only one or two load categories, such as wind and solar are used only in mid-load.

The framework of NEWAGE enables the analysis of impacts of different political interventions on macro-economic indicators, such as GDP growth, sectoral gross value added (GVA), employment and competitiveness. Specifically, for the coupling procedure, we also calculate regional net income, calculated as the sum of income from capital and labor minus payments of taxes to the government, and regional utility, defined as the total consumption by households.

2.2. Integrated Assessment Toolbox

In this section, the links between the energy system model, TIMES PanEU, the health impact assessment model, EcoSense, and the general equilibrium model, NEWAGE are presented. The three models are coupled with TIMES PanEU at the core; the respective data exchange and links are shown in Figure 2.

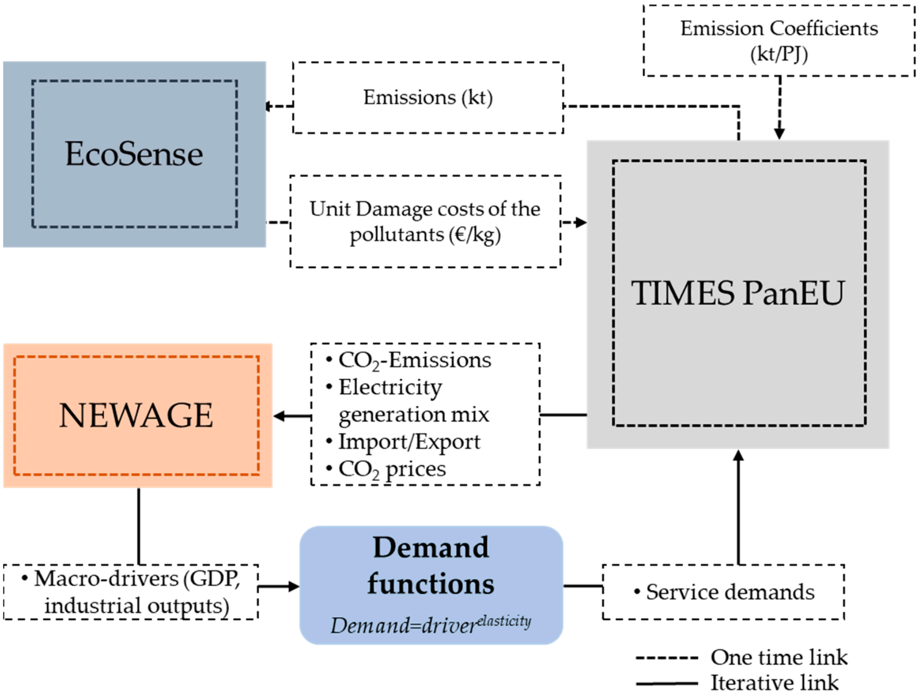

Figure 2. Integrated Assessment Toolbox—links between the models.

2.2.1. Linking Energy System Model with Health Impact Assessment Model

We developed a link between the TIMES PanEU energy system model and the health impact assessment model EcoSense to analyze the interaction between GHG mitigation and air pollution and to assess the health impacts from energy-related emissions. The impacts of such a link on the energy transition have already been analyzed in different studies [3,8]. The link itself is depicted in the upper part of Figure 2, together with the relevant data exchange.

In a first step, common assumptions of both models, such as population growth and general socio-economic developments are harmonized. Most importantly, the time horizon, milestone years and monetary base year are matched. Similarly, the different sectors in TIMES PanEU are matched to specific emission source categories in EcoSense, differentiating different release heights as well as mobile and stationary source (Since we only consider country specific damage costs in this study without any sectoral differentiation, this match was actually not necessary). As a following step, the existing emission coefficients (kt/PJ) of air pollutants (SO_2, NO_x, CO, NMVOC, $PM_{2.5}$, PM_{10}) are updated in TIMES PanEU to reflect the latest developments and emission standards induced by the Clean Air Policy Package [35]. The coefficients are disaggregated according to sectors, regions, technology and fuel types [32]. Based on these coefficients, TIMES PanEU provides to EcoSense sector- and country-specific total emissions (kt) for each pollutant. By utilizing the data from TIMES PanEU, EcoSense calculates unit health damage costs (€/kg). These are disaggregated according to different pollutants without sectoral decomposition and fed back to TIMES PanEU.

The unit health damage costs are implemented as an additional parameter and the total health damage costs are calculated in the model according to the following equations [36]:

$$\mathrm{DAM}\ (\mathrm{EM}) = \alpha * \mathrm{EM}\ (\beta + 1) \tag{1}$$

where:

EM (kt) is the emission in the current period,

DAM (EUR/kt) is the health damage cost in the current period,

$\beta \geq 0$ is the elasticity of the marginal health damage cost to amount of emissions,

$\alpha > 0$ is a calibrating parameter, which may be obtained from dose-response studies that allow the computation of the marginal health damage cost per unit of emission at some reference level of emissions.

If the marginal cost at the reference level is denoted with MC_0, the following holds:

$$MC_0 = \alpha * (\beta + 1) * EM_0 (\beta) \tag{2}$$

which is what is calculated by EcoSense according to the link between the models.

When there is no elasticity factor assumed ($\beta = 0$), i.e. when there is a linear relationship between health damage costs and amount of emissions, the first equation can be simplified as follows:

$$DAM (EM) = (MC_0 * EM_0) * EM \tag{3}$$

The cost figures (MC_0) are calculated for each region in TIMES PanEU according to milestone years. The range of cost figures according to countries and sector disaggregation is available in [32].

The health damage costs can be used for two types of assessments in energy system modelling:

- To provide an exogenous economic evaluation of the health damage by the energy system, without any feedback to the cost-optimization function (ex-post);
- To study how the optimal energy supply mix would change, if health damage costs were to be internalized, as part of the cost-optimization function (ex-ante). This would correspond to a scenario in which the health damage costs of air pollutants are considered in the energy system design.

Both types of assessment are carried out as a part of our study and insights are given in Section 3. An iteration between TIMES PanEU and EcoSense is not required for the conducted scenario analysis as there are not any feedbacks to be iterated between the models. Due to the linear relationship between the total health damage costs as calculated by EcoSense and the total emissions, the unit costs are independent of the absolute amount of emissions and climate mitigation policies. This means that the values are scenario-independent as well.

2.2.2. Linking Energy System with General Equilibrium Model

The main objective of the link between TIMES PanEU and NEWAGE is to compensate the limitations of each model through their cooperative work. The structure of NEWAGE, in which production sectors are interconnected, depicts in a transparent manner the variations caused by decarbonization in GDP development and sectoral growth, which modifies the demand for energy services. TIMES PanEU can, in return, use the results from NEWAGE to update its own sectoral demand for energy services. Following this, TIMES PanEU uses its highly detailed depiction of the energy system to provide a more accurate electricity mix back to NEWAGE. The link between the two models is intended to happen after the link between EcoSense and TIMES PanEU to complete the integrated assessment toolbox, where the synergies between air pollution control and energy transition are already taken into account (ex-ante). The data exchange between the two models is presented in the lower part of Figure 2.

Before initiating the iteration process, NEWAGE and TIMES PanEU need to harmonize their socio-economic assumptions. To do so, projections about population and GDP growth are compiled to a common reference scenario (the respective scenario assumptions are explained in Section 2.4), which is implemented in both models together, following the method proposed in [37]. Additionally, NEWAGE is calibrated to the technology development of TIMES PanEU by replicating its sectoral CO_2 emissions and electricity mix of the chosen reference scenario. The harmonization and calibration process is supposed to ensure comparability between the results from both models.

The iteration process (Figure 2) begins with TIMES PanEU, as it produces the first results of the electricity-generation mix. Following, NEWAGE is set for the designed scenario and fixes, with a small deviation margin, its electricity generation mix to be at the same level as that from TIMES PanEU. Next, NEWAGE produces results for GDP development, sectoral GVA, net income and utility. Finally, the existing sectoral energy service demands in TIMES PanEU are updated according to Equation (4) and the sectoral match between the models given in Table A3 in Appendix B. As there are feedbacks between the models with the updated energy service demands in TIMES PanEU and electricity mix in NEWAGE, the two models are run iteratively. Although the relation between energy use and economic developments has already been proved in [2], it is also discussed in [38] that energy service demand values are not only affected by the economic developments in a country. There are factors such as population growth, efficiency improvements, energy production and transportation of energy which also influence the energy service demand development. Additionally, the impact of social factors such as comfort, behavior or happiness should also be considered. Therefore, we apply a decoupling factor *DF* to balance the impact of macro-economic variations and other impacts on the energy service demands, which also reflects a certain degree of demand inelasticity in energy services:

$$ED^{SCE}_{s,(x+1)} = \left(\frac{EV^{SCE}_{i,x}}{EV^{REF}_{i}}\right)(1-DF) + ED^{REF}_{s}DF \tag{4}$$

In Equation (4), ED denotes the energy service demands of sector s in iteration x and scenario SCE, while REF denotes the reference scenario. EV designates the level of the economic variable i, which is related to sector s according to Table A3 in Appendix B. As mentioned, DF represents the decoupling factor, which determines the weight that the sectoral energy demands from the reference scenario will have on the updated values. Thus, if a decoupling factor of 25% is applied, it is assumed that 75% of the demand development is reflected by the general economic development, while 25% are mainly influenced by other factors, such as efficiency gains, changing consumption patterns or population.

To summarize, the steps of the iteration process are the following:

1. TIMES PanEU provides the results of the electricity mix calculated for a decarbonization scenario to NEWAGE as shown in Figure 2. The technology match for this step between the models is given in Table A4. in Appendix B.
2. NEWAGE calculates economic variables influencing energy service-demand growth patterns based on the provided results by TIMES PanEU.
3. Energy service-demand projections are updated in TIMES PanEU based on chosen economic variables as calculated by NEWAGE.
4. The convergence criterion is computed.
5. If convergence criterion is not within the range of convergence, go back to step 1.

In this study, we use the relative variation of GDP from NEWAGE between the iterations as the convergence criteria. This choice is based on the fact that GDP is a product of all production sectors and consumption, so it stops varying when other economic variables in NEWAGE reach convergence. A derivation of ± 0.005% is assumed to be sufficiently small to account for convergence.

2.3. Decomposition Analysis

In this study, we apply decomposition analysis to identify relevant decarbonization drivers and understand their impacts on the decarbonization of the energy system with also an explicit focus on the differences resulting from the links with an impact assessment and general equilibrium model. Similar to the other studies reviewed in Section 0 [9–11], we also opted for LMDI as the basic method, since this guarantees full decomposition without any residual emissions [10].

CO_2 emissions in the overall system are decomposed into four different effects in our study, following a similar approach as in [9]: Activity effect, structure effect, fuel-intensity effect and carbon-intensity effect. The activity effect refers to the changes in CO_2 emissions due to variations in energy service demands. In our study, the link with the general equilibrium model NEWAGE affects the energy service demands which enables the model to take into account the macro-economic variations during the energy transition. Structure effects describe emission changes because of the technological switch. The building of a solar power plant to replace the power generated by a decommissioned coal power plant can be given as an example of this effect. The fuel intensity effect defines the difference in CO_2 emission due to switching to more efficient technologies without changing the energy carrier. One example of this effect is the replacement of a gasoline car in the transport system with a more efficient gasoline car. Differences from changing the carbon content of fossil fuels are captured by the carbon intensity effect, for example changing an oil boiler with a gas boiler in the residential sector. Based on this decomposition total CO_2 emissions in the energy system can be formulated as follows [9]:

$$\mathrm{CO}_{2,\text{ total system}} = \sum_i activity_i * \left(\sum_j \frac{activity_{i,j}}{activity_i} * \frac{fuel_{i,j}}{activity_{i,j}} * \frac{CO2_{,system,i,j}}{fuel_{i,j}} \right) \tag{5}$$

Activity is the energy service demand in PJ here and i refers to sector and j to technology in Equation (5). When the equation is rewritten as in Equation (6), where a represents the demand, s does the structure, f does the fuel and c does the carbon content. The changes in CO_2 emissions can be also described with Equation (7):

$$\mathrm{CO}_{2,\text{ total system}} = \sum_{i,j} a_i * s_{i,j} * f_{i,j} * c_{i,j} \tag{6}$$

$$\Delta\, \mathrm{CO}_2 = \Delta \text{ demand change} + \Delta \text{ structural shift} + \Delta \text{ efficiency improvements} + \Delta \text{ fossil fuel switching.} \tag{7}$$

2.4. Scenario Structure and Assumptions

To analyze the impacts of different variables through the energy transition, we investigate a scenario with a Europe-wide target to reduce greenhouse gas (GHG) emissions across all sectors and all the member states in EU28 in 2050 by at least 85% compared to 1990 levels. To allow for a continuous reduction over the years, we implement the milestones displayed in Table 1. To achieve these targets in 2050 and ensure a smooth and realistic transition path, additional milestones are set in 2030 and 2040. These milestones are determined according to given targets in [2]. In Table 1, the reduction targets are also given according to the emission level in 2015 as this is the reference year in this study.

Table 1. Milestone targets of the analyzed reduction scenario.

Year	GHG Reduction Target Milestones Rel. to 1990 Levels	GHG Reduction Target Milestones Rel. to 2015 Levels
2030	50%	35%
2040	70%	55%
2050	85%	81%

The EU reference scenario [22] is used to define the socio-economic assumptions as a basis for the reference scenario utilized in this study. Both models harmonized their relevant assumptions accordingly, including decarbonization targets in TIMES PanEU and GDP development in NEWAGE. Furthermore, technology development in NEWAGE is calibrated to the respective TIMES PanEU results of this reference scenario.

For the link with EcoSense, the health-damage cost factors are introduced into the energy system model starting from 2020 as the base year of the model is 2015 and these costs are not taken into account in the system design in reality. It is also assumed that these costs are phased in gradually, with only half of the actual health-damage costs applied in 2020. This stepwise introduction also matches with the 5-year model structure of TIMES PanEU [3]. From 2030 on, the unit health damage cost (€/kg) values calculated by EcoSense are employed directly in the model.

Aside from the given decarbonization targets for Europe, NEWAGE, as a world model, also needs to make assumptions about decarbonization efforts in the rest of the world. For the reference scenario, an emissions path consistent with the reference technology scenario (RTS) from the Energy Technology Perspectives (ETP) 2017 study [39] was assumed. For the remaining scenarios, the targets are diverse and represent a coalition between regions that want to pursue higher GHG reductions than in the business-as-usual scenario. Detailed targets are described in Table A1.

As the aim is to take into account all the different drivers in the energy system development, TIMES PanEU is first linked with EcoSense. Here two scenarios are defined to address the impacts of having damage costs in TIMES PanEU. In the GHG scenario (Table 2), damage costs are not considered in the optimization function (ex-post). In the GHG_DAM scenario, damage costs are considered in the optimization function (ex-ante) and only this version is finally used in the iterations with NEWAGE as given in Table 2. As there is also no scientific consensus on how much energy service demands are solely influenced by economic development or on how big of a role other socio-economic parameters and developments play, we conduct a sensitivity analysis and apply three different decoupling factors for the link between TIMES PanEU and NEWAGE: 25%, 50% and 75%. These scenarios refer to the integrated assessment toolbox (IAT). Together with the stepwise coupling of the three models, this results in a total of six scenarios, which are also described in Table 2.

Table 2. Modelled scenarios and their abbreviations.

Abbreviation	Description	Applied Models
Reference	Business as usual (EU reference scenario)	TIMES PanEU; NEWAGE
GHG	85% GHG reduction	TIMES PanEU
GHG_DAM	85% GHG reduction in the EU28 and health damage costs are internalized as part of the optimization function (ex-ante)	TIMES PanEU + EcoSense; NEWAGE
IAT_25	85% GHG reduction in the EU28, health damage costs are internalized as part of the optimization function (ex-ante), 25% decoupling factor	IAT [1]
IAT_50	85% GHG reduction in the EU28, health damage costs are internalized as part of the optimization function (ex-ante), 50% decoupling factor	IAT [1]
IAT_75	85% GHG reduction in the EU28, health damage costs are internalized as part of the optimization function (ex-ante), 75% decoupling factor	IAT [1]

[1] TIMES PanEU + EcoSense + NEWAGE.

The following technical assumptions are applied in the scenario structure in TIMES PanEU across all the scenarios in Table 2:

- The electric vehicles cost assumptions are developed according to the learning curve approach to calculate the cost of the battery packs in the vehicles. A learning rate of 16% is assumed, according to [40].
- The decommissioning curves of the existing nuclear power plants are determined based on [41].
- Energy-efficiency technical measurements in industry are included as an option based on [21].
- Existing and forthcoming electricity exchange capacities are taken from [41].
- Livestock emissions are included in all the pathways based on [42].
- Fuel price assumptions are taken from [18].
- Heat-saving processes and their potential in residential buildings are included according to [43].
- Techno-economic assumptions such as investment cost, variable costs, availability factors assumptions for solar PV, wind on-shore and off-shore, tidal and wave energy are in line with [22] for the reference scenario. According to deployment scenarios of these technologies,

higher cost reductions might be expected [44]. Therefore, techno economic assumption of these technologies are taken from [44] for the other scenarios structured according to Table 2.

3. Result

In this section, we follow the order of the integrated assessment toolbox building process to discuss our findings. In Section 3.1., we present insights from the internalization of the externalities in the energy system. Impacts of the macro-economic variations with the link through NEWAGE are explained in Section 3.2. In this sub-section, insights gained through the iteration process and the effect of different decoupling factors are discussed in detail as well. We conclude the section with findings from the decomposition analyses for the entire energy system together with the remaining CO_2 emissions and sectoral decomposition of transport.

3.1. Impact of Externalities in the Energy System

In the integrated assessment toolbox that is built, air pollutants and their health damage costs are integrated into TIMES PanEU through the link with EcoSense. By comparing the reference, greenhouse gas (GHG) and greenhouse gas damage (GHG_DAM) scenarios, co-benefits and interactions between decarbonizing the energy system and air pollution mitigation can be identified. As there are associated uncertainties especially with the absolute values of damage costs integrated in TIMES PanEU, only relative differences to the reference scenario can be interpreted to provide relevant and meaningful insights from their integration.

Before internalizing the health damage cost in the system in 2020, no significant differences are observed between the Reference and GHG scenarios. However, the GHG reduction target results in better air quality and consequently in savings in health damage costs after 2020 (Figure 3, ΔGHG). In 2030, all cost savings occur mainly in three sectors: supply, electricity and industry. The sector descriptions and their scope are given in Section 2.1.1. Lower utilization of the gasification processes creates the difference in the supply sector. Higher deployment of renewables helps to clean up electricity and industry sectors, not only with regard to GHG but also with regard to air pollutants. Later, savings are also achieved from changes in the residential sectors. As one of the main existing heating technologies, new oil boilers are still deployed in the reference scenario. Although they are characterized by improved efficiency, they still emit high levels of GHG and air pollutants. Hence, they are replaced with cleaner heating technologies such as heat pumps in the GHG scenario, which also further reduces emissions of air pollutants along with the health damage costs. With the internalization of the health damage costs in the optimization function (GHG_DAM), this replacement accelerates; therefore, earlier reductions and cost savings are seen compared to the GHG scenario. Similarly, the introduction of the health damage costs in the optimization function leads to an early coal exit in the residential sector, which results in visible savings already in 2030. Additionally, less biomass utilization and, in turn, a higher rate of other renewables, help to further reduce damage costs associated with air pollution from the residential sectors. Compared to the reference scenario, savings in health damage costs caused by changes in agriculture can be observed in both of the scenarios, though they are more visible when these costs are internalized in the optimization function (GHG_DAM). The savings are mainly the result of utilizing fewer petroleum products. Again, internalizing health damage costs (GHG_DAM) reduces the biomass consumption, not only in residential and agriculture but also in industry and electricity, which results in a slightly higher level of cost reduction in this scenario. A detailed analysis of the related changes in the energy system and the respective levels of air pollution are also given in [3,32].

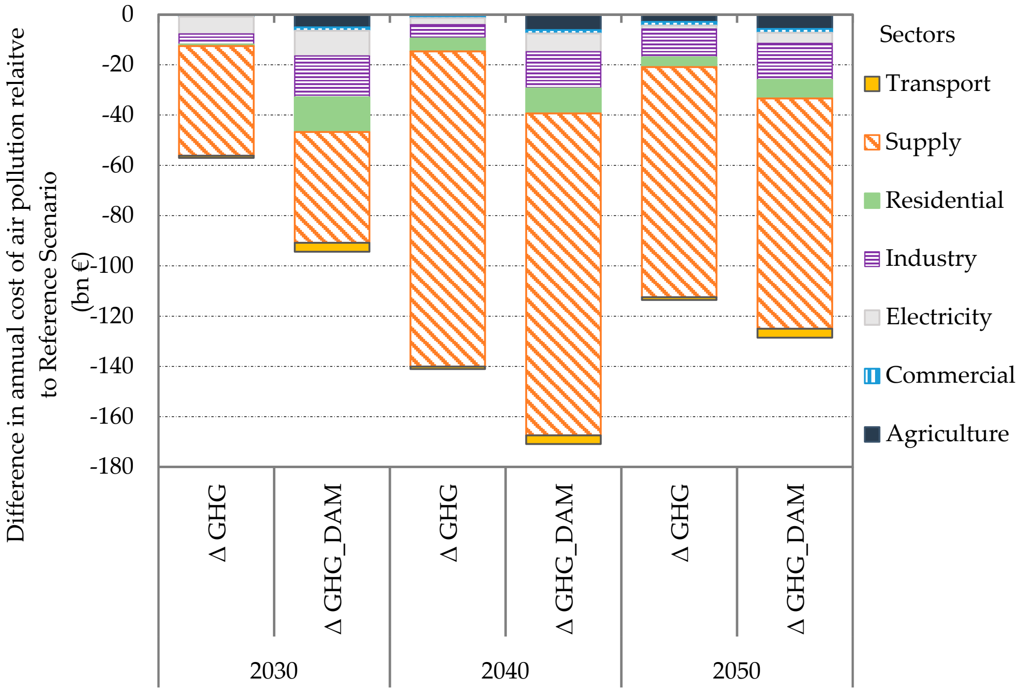

Figure 3. Difference in annual costs of air pollution relative to the reference scenario in the European Union (EU28, bn €2010).

The impact of internalizing health damage costs can also be seen in the marginal CO_2 mitigation cost (Figure 4). Introducing health damage costs to the system (GHG_DAM) brings lower marginal CO_2 mitigation costs, especially in the early years. With increasing ambition to reduce GHG emissions over the time horizon, however, the reduction target itself becomes more dominant and the additional benefit of lower marginal CO_2 mitigation costs diminishes (2030 difference vs. 2050 difference in Figure 4).

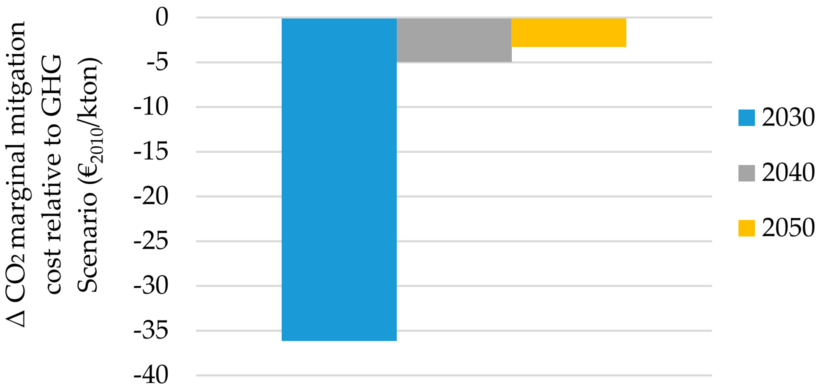

Figure 4. Difference in marginal CO_2 mitigation cost in greenhouse gas damage (GHG_DAM) scenario and greenhouse gas (GHG) scenario in the EU28 (€2010/kton).

The reductions in externalities achieved, which are reduced GHG emissions and savings in damage costs, are partly compensated for by higher cumulated, discounted system costs, presented as net present value in 2015 (NPV 2015) in Figure 5. Despite these higher systems costs, both the GHG and GHG_DAM scenarios achieve net benefits in social costs compared to the Reference scenario. Increased innovation effort is assumed to occur in the case of GHG mitigation targets, which is reflected by more progressive techno-economic developments and assumptions in the corresponding scenarios as explained in Section 2.4. Therefore, this effort can offset the additional push needed to decarbonize the energy system resulting in almost identical system costs in the GHG and the reference scenario. Regarding the total social costs as the sum of system and health damage costs, the GHG scenario still shows a benefit of 596 bn€ from total social cost through savings in total damage costs compared to the Reference scenario. These are even higher in the GHG_DAM scenario where the health damage costs are internalized, although partly being compensated by increased system costs. Compared to the GHG scenario, internalizing health damage costs of air pollutants still results in additional benefits of 333 bn€ which leads to the lowest social costs between the three scenarios considered.

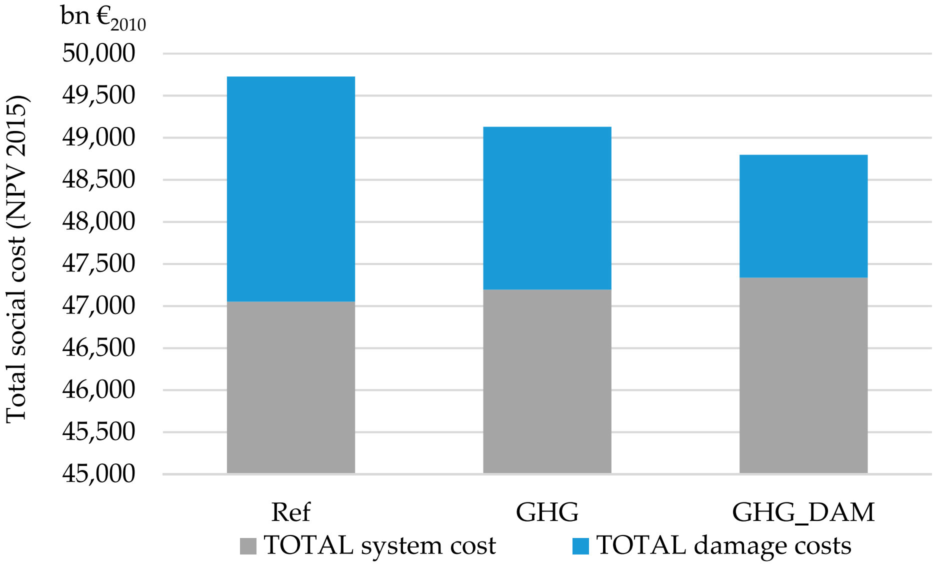

Figure 5. Total social cost in the EU28 (bn €, 2010).

3.2. *Impact of Macro-Economic Variations in the Energy System*

In this sub-section, we discuss the impact of macro-economic variations in the energy system with the introduction of a carbon cap and trade system. We begin by presenting the selected indicators and their development from the general equilibrium model to show how the different economic variables are affected by a carbon cap and trade system which reasons the different energy service demands developments in the energy system. In the following sub-section, we provide insights from the iteration process between the energy system model and the general equilibrium model and the impact of applying different decoupling factors. We conclude the section by analyzing the selected indicators from both of the models after the models are converged.

3.2.1. Impact of a Carbon Cap and Trade System on the Economy

Compared to the reference scenario, lower CO_2 emission caps are introduced in GHG_DAM scenario after the year 2020. As expected, the lower availability of certificates in the market has significant effects on the economy, as shown in Figure 6. This Figure is produced with results from NEWAGE using the same electricity generation mix as TIMES PanEU for this scenario, but before starting the iteration process. GDP levels are lower in GHG_DAM, compared to the reference scenario, by 1.5% in 2030 and 3.2% in 2050. On the other hand, the gap between the two scenarios in net income is decreasing with time, from −1.4% in 2030 to −0.7% in 2050, as the revenues from emission certificates are paid back to the consumers in the form of a lump sum.

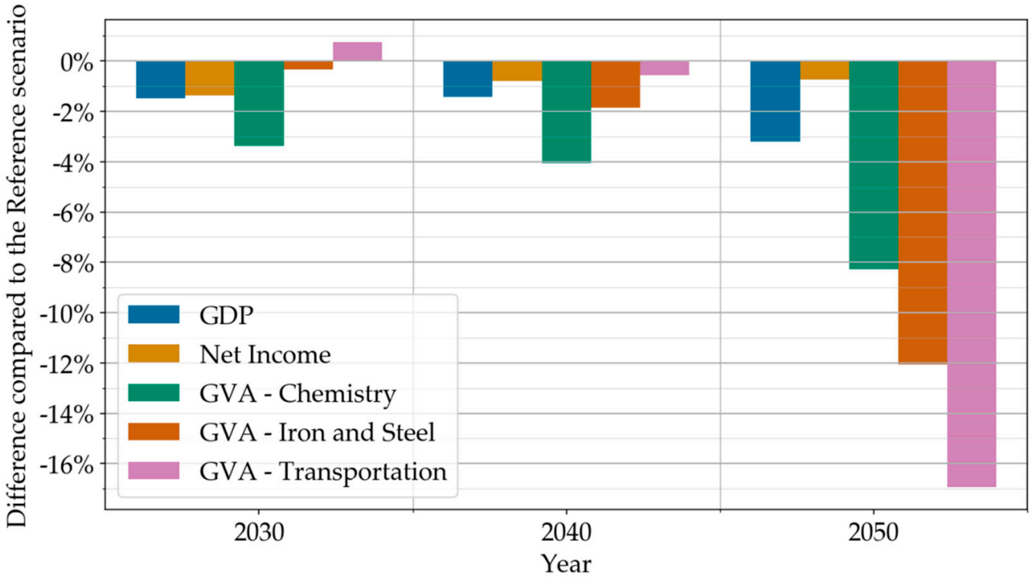

Figure 6. Values of selected economic variables in the EU28 for GHG_DAM compared to the reference scenario.

Regarding industrial production, we show the GVA variations of the chemical and iron and steel industries as they are energy-intensive sectors with a high consumption of fossil fuels. This makes them more vulnerable to the scarcity of emission allowances. In Figure 6, it can be seen that the impact of the emission targets on these sectors is higher than the impact on GDP development. GVA of the chemical industry in GHG_DAM is 3.4% lower than the reference scenario in 2030 and 8.3% lower in 2050. Additionally, GVA of iron and steel in GHG_DAM is 0.3% lower in 2030 and 12% lower in 2050, compared to the reference scenario.

The last economic variable displayed in Figure 6, is the GVA of the Transportation sector, which includes transportation of goods and passengers (without private individual transportation) by land, air and water. In the GHG_DAM scenario, this sector has a GVA level 0.8% higher than the reference scenario in 2030, because the energy-intensive sectors consume less fossil fuels which makes them cheaper in the near-term. Yet, in 2040 and 2050 the GVA levels are 0.6% and 17%, respectively, lower than the reference scenario due to high costs to substitute fossil fuels and lack of alternatives for decarbonization.

3.2.2. Iteration Process Between TIMES PanEU and NEWAGE and Impact of Decoupling Factor

As discussed in Section 3.2.1., having a carbon cap impacts economic variables. To reflect these impacts on the energy system, we link TIMES PanEU with NEWAGE. As explained in Section 2.2.2, during the linking of the models, we apply a decoupling factor. In this section, we discuss the effects that different decoupling factors have on the coupling process between TIMES PanEU and NEWAGE. To illustrate these effects, we depict the development of the convergence criterion and the variation of parameters exchanged between models per iteration.

In Table 3, upward arrows indicate a positive deviation higher than the upper margin of the range of convergence, downward arrows indicate a negative deviation lower than the lower margin and an arrow pointing to the right indicates the error is within the range of convergence. As seen in Table 3, if the decoupling factor is less than 50% the models are able to converge at the early iterations. The convergence criterion reaches the acceptable range after the third iteration in IAT_25 and IAT_50 scenarios. The lower the decoupling factor, the greater is the weight of NEWAGE results given as input to TIMES PanEU. Therefore, the models are able to convergence earlier. On the other hand, with higher decoupling factors the exchange between the models is limited and more iterations are required for the models to converge.

Table 3. Deviation of gross domestic product (GDP) between iterations for three decoupling factors.

Scenario	1	2	3	4	5	6
IAT_25	-	↓ −0.3501%	↓ −0.0164%	→ 0.0011%	→ −0.0020%	→ −0.0005%
IAT_50	-	↓ −0.2816%	↑ 0.0051%	→ 0.0028%	→ −0.0042%	→ 0.0014%
IAT_75	-	↓ −0.2181%	↑ 0.1326%	↓ −0.1189%	↓ −0.0063%	→ 0.0021%

The impact on the iteration process of a decoupling factor higher than 50% can be also seen on the selected energy service demand developments during the iteration process. As the impact of the coupling factor on the number of iterations is not visible between 25% and 50%, energy service demand (Figure 7) between the iterations are shown for IAT_50 and IAT_75 scenarios. The depicted variations are always relative to the previous iteration; the connecting lines provide an easily understandable visualization of the convergence progress. In the IAT_50 scenario, the highest variations are observed between iterations 1 and 2 (−7.5% to −10%) and iteration 2 and 3 (−1% to +2%). Although the iteration process takes longer in the IAT_75 scenario, the variations between the iterations (up to −7.5%) are smaller compared to the IAT_50 scenario. Similar to the GDP development in Figure 6, energy service demands do not change significantly after the 4th iteration; however, small variations are observed in the IAT_75 scenario until the 6th iteration. In both of the scenarios, after a sharp reduction in the second iteration, slight increases are experienced until both models reach convergence. Because of the limited data exchange, stronger fluctuations are observed in scenario IAT_75.

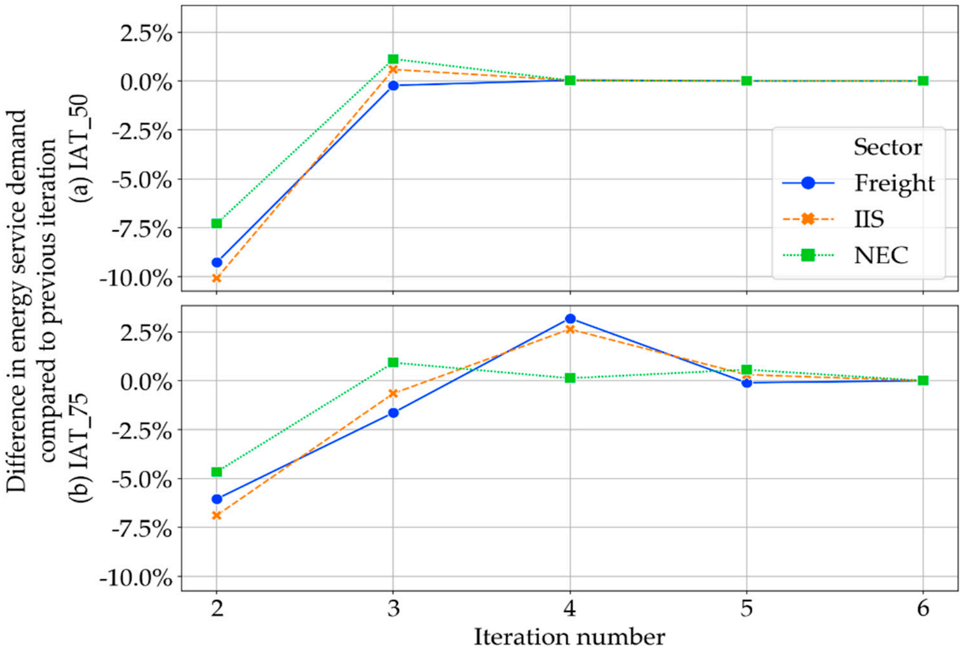

Figure 7. Difference (%) in the selected energy service demand developments in the EU28 compared to previous iteration for (**a**) IAT_50 and (**b**) IAT_75 in 2050.

The electricity generation mix used as input in NEWAGE displays a similar development to the one shown in Figure 7. Figure 8 presents the difference in electricity generation per technology as implemented in NEWAGE in the EU-28 in 2050 for each iteration step. For a decoupling factor of 50% (Figure 8a) major differences are seen between iterations 1 and 2 and between iterations 2 and 3. Similar to the development of the energy service demands in Figure 8b, there are major differences between all iterations with the exception of the last. These results illustrate again the effects of the decoupling factor, not only on the convergence criterion but also on the input variables used by NEWAGE based on the data exchange with TIMES PanEU.

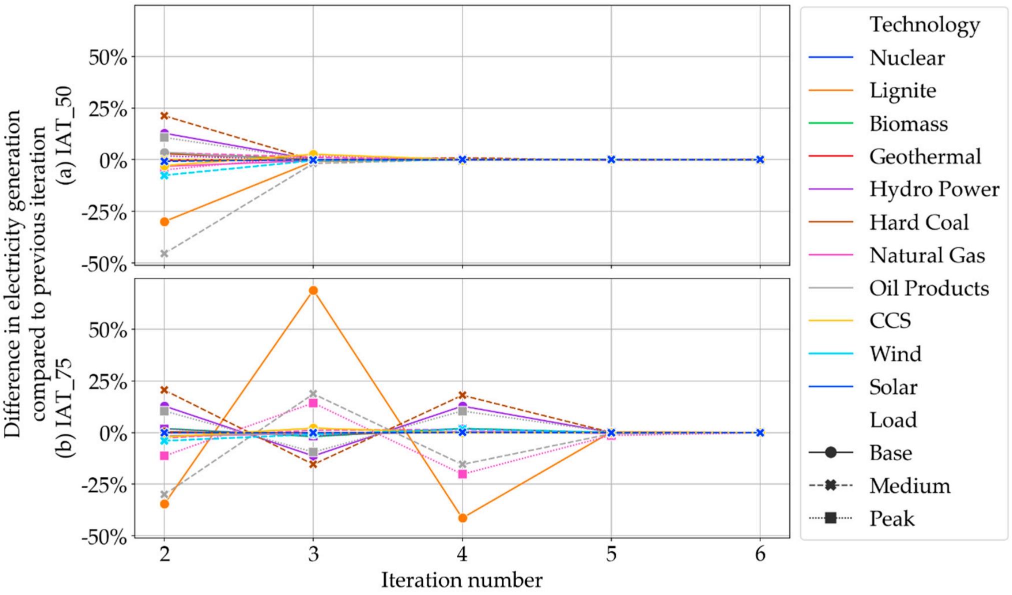

Figure 8. Difference (%) in electricity generation in the EU28 compared to previous iteration for (**a**) IAT_50 and (**b**) IAT_75 in 2050.

The decoupling factor not only has an impact on the number of iterations but also on the final level of energy service demands taken as input to TIMES PanEU once the models reach convergence as presented in Table 4. For consistency, we again choose the exemplary sectors as depicted in Figure 7. Compared to the GHG_DAM scenario, which does not consider any economic variation, the lowest decoupling factor brings the highest change in energy service demands. The higher the decoupling factor, i.e. the lower the influence of economic developments on energy services is anticipated, the lower are the changes in the energy service demands, with the IAT_75 scenario experiencing only limited changes of less than 5%. Nevertheless, all three scenarios show a reduction in demand, suggesting that economic development under a carbon cap and trade system affects demand development negatively. Iron and steel (IIS) energy service demand reduces more than 14% in IAT_25 and around 9.5% in IAT_50. A similar trend is observed and the reduction is seen around 5% in IAT_75. Between the scenarios, the impact of the decoupling factor is directly reflected in the demand development variations. Similar impact is also seen at the GDP calculated by NEWAGE when the models reach convergence. Similar to energy service demand values, highest variation is seen in IAT_25 scenario, while the smallest variation is observed in IAT_75 scenario.

Table 4. Difference in selected energy service demands and GDP relative to GHG_DAM scenario in 2050 in the EU28.

Scenarios	**TIMES PanEU**			**NEWAGE**
	Freight	**NEC**	**IIS**	**GDP**
Δ IAT_75	−4.72%	−3.10%	−4.74%	−0.21%
Δ IAT_50	−9.43%	−6.21%	−9.51%	−0.28%
Δ IAT_25	−14.08%	−9.30%	−1.,24%	−0.37%

3.2.3. Energy System Analysis

In this section, we explore the differences between scenarios for the selected indicators in the energy system after the models reach convergence with different decoupling factors.

According to Figure 9, industry and transport are the main sectors in which final energy consumption is affected by economic variations. According to the sectoral match in Table A3 (Appendix B), the industrial sectors have their direct respondents in both of the models. Therefore, impacts from the cap-and-trade system on the sectoral development of these sectors are higher compared to other sectors in NEWAGE, as can also be seen in Figure 6. Consequently, higher reduction is also observed in TIMES PanEU results in this sector for the final energy consumption.

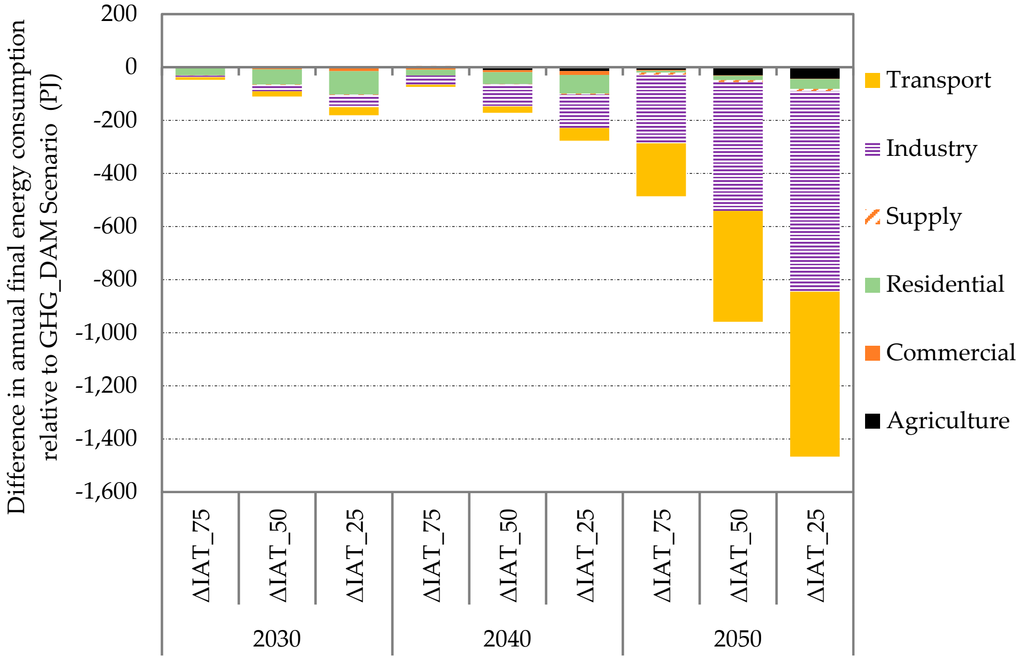

Figure 9. Difference in annual final energy consumption by sector relative to GHG_DAM scenario in the EU28 (PJ).

Transport is another sector that reacts sensitively to a cap-and-trade system in NEWAGE as explained in Section 3.2.1. Again, the GVA of this sector is highly affected by a carbon cap. The sectoral match between TIMES PanEU and NEWAGE reflects this development from NEWAGE on the public transport modes in TIMES PanEU. The impact on the transportation from the NEWAGE results is also clearly visible in the final energy consumption change of this sector in TIMES PanEU.

The impacts of cap-and-trade system in NEWAGE for economic variables such as services, utilities and net income are limited compared to other sectors (Figure 6). The changes on the final energy consumption in residential and commercial based on their sectoral match with these sectors are minor compared to industry and transport especially in 2050. However, in the early periods such as in 2030 and particularly in residential, slightly higher differences are seen compared to the GHG_DAM scenario. In NEWAGE, the revenues from emission certificates are paid back to the consumers in the form of a lump sum in the late periods. Therefore, the services and net income are mainly affected in the early periods but in the late periods they also benefit. Furthermore, residential and commercial are not as energy-intensive and do not depend as much on fossil fuels as industry and transportation. Hence, they are not as vulnerable to changes in electricity production, emission caps and CO_2 prices in NEWAGE. The lower changes in final energy consumption in residential and commercial also reflect the lower demand elasticity typically observed in these sectors compared to industry. As energy consumption in residential and commercial is mainly characterized by basic needs (space heating and hot water), respective demand is typically reacting slower to economic variations compared to, for example, industrial sectors.

Figure 10 shows the reduction in the primary energy consumption in the system after the link with NEWAGE. Due to the decarbonization targets, the shares of the conventional energy carriers such as petroleum products and coal are already limited in later periods. Therefore, decreasing energy service demands affect mainly the amount of renewables in the system. As the lower decoupling factor brings higher reductions on the energy service demand, again similar to Figure 9, the highest reductions are seen in the IAT_25 scenario and the lowest is seen in the IAT_75 scenario. Due to decreasing demand in industry, electricity demand also diminishes in industry. Therefore, higher reductions in hydro, solar and wind can be explained with the lower electricity generation in the system. Reduction of biomass in 2050 in IAT scenarios partly comes from the transport sector. Energy service demand reduction in public transport diminishes the total use of biomass in this sector as well.

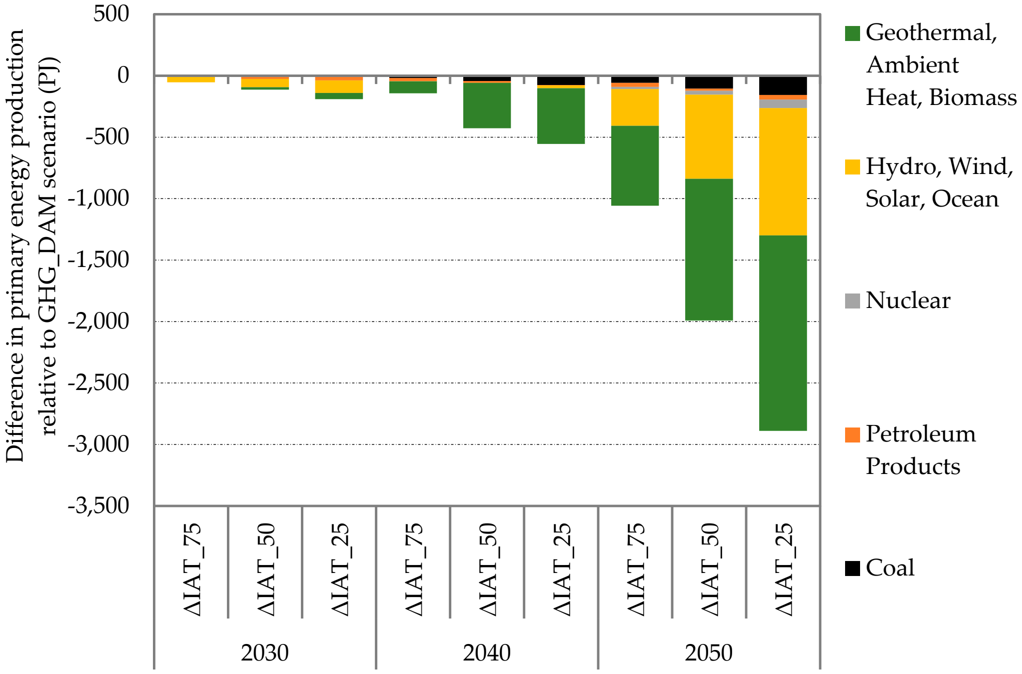

Figure 10. Difference in primary energy production relative to GHG_DAM scenario in the EU28 (PJ).

Unlike the impact of internalizing health damage costs (Figure 4), the effects of adopting the economic variations to energy system on CO_2 mitigation cost appear in the later periods as the impact of the cap-and-trade system on the economy becomes also more visible in 2050 (Figure 6). Therefore, variations on final energy consumption as well as CO_2 mitigation costs are also seen clearly in the later periods compared to early periods (Figure 11). Since the highest reduction in energy service demands as well as in the final energy consumption is experienced in the IAT_25 scenario, the same effect is also seen on the CO_2 mitigation cost to achieve the given reduction target in the system. The difference in the CO_2 costs is limited in the IAT_75 scenario due to the limited exchange between the models which leads to lower variations in energy service demand developments.

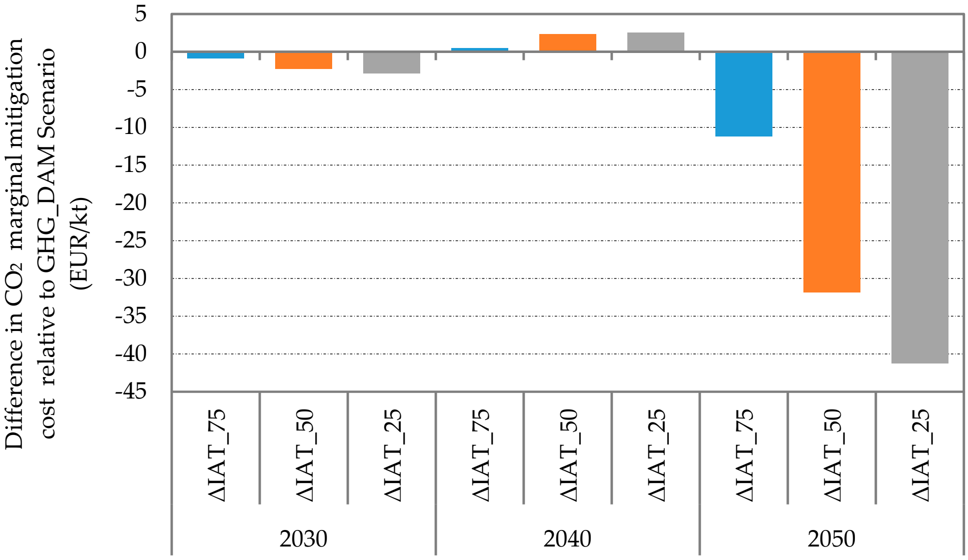

Figure 11. Difference in CO_2 marginal mitigation cost relative to GHG_DAM Scenario in the EU28 (€/kt).

Figure 12 depicts selected economic variables for the three scenarios with different decoupling factors, namely IAT_25, IAT_50 and IAT_75, compared to GHG_DAM based on results from NEWAGE. It is possible to see that the decoupling factor usually has a low impact on the level of the chosen variables. The variation between the three scenarios is usually lower than 0.25%, with the only exception being the CO_2 prices for IAT_25. Overall, the coupling process decreases demand for fossil fuels, resulting in lower CO_2 prices and lowering the revenues received by households and their net income. With a lower income, households consume less and GDP decreases. On the other hand, the lower CO_2 prices help to increase sectoral production from energy-intensive sectors, as seen by GVA values of iron and steel and chemical sectors. Finally, this extra sectoral production is used mainly for the internal European market, since imports and exports reduce, and the lower volume of international trade contributes to the reduction of GVA from the transportation sector.

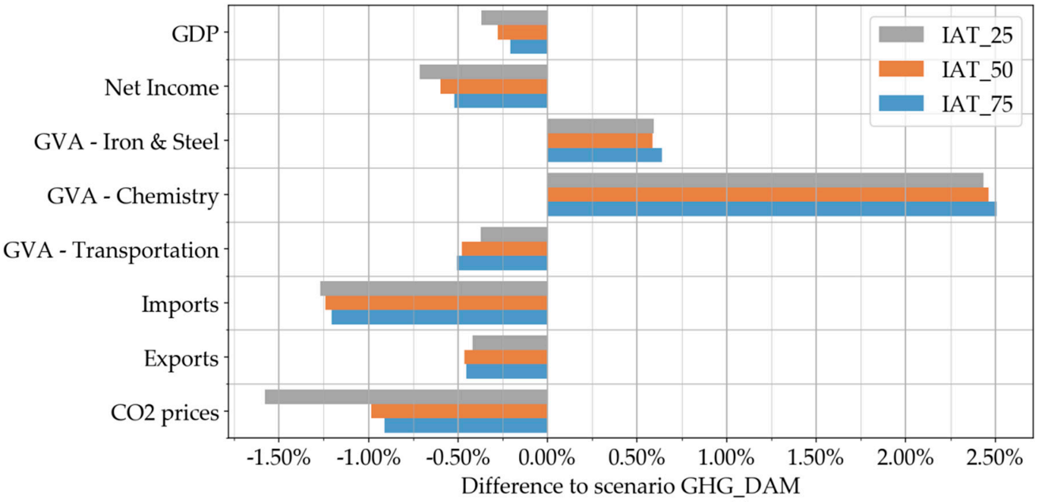

Figure 12. Difference of selected economic variables in the EU28 compared to GHG_DAM in 2050.

Regarding scenario-specific variations, IAT_75 produces slightly higher CO_2 prices, net income, GDP and sectoral production than the other two. IAT_25, on the other hand, lead to lowest CO_2 prices, net income, GDP and sectoral production compared to the other two.

3.3. Decomposition Analysis

This sub-section assesses the decomposition of CO_2 emission reduction in the energy system according to the given reduction target based on the reference scenario in our study. In Section 3.3.1., the remaining CO_2 emissions in each sector are analyzed to identify the sectors which are more difficult to decarbonize compared to others. In the following section, considering the health damage costs and macro-economic variations, decomposition analysis and the share of different mitigation options in different scenarios are discussed. The last section presents a decomposition analysis of a specific sector, transport, to pinpoint the role of sector-specific mitigation options.

3.3.1. CO_2 Emissions-Reduction Paths

Without additional ambitious reduction targets in the energy system (reference scenario), CO_2 emissions in the supply and industry sectors experience even increases in the early periods and this increase continues in the supply sector until 2050. The increase in the supply sector can be explained with the application of gasification processes in the reference scenario. In this scenario, only Emission Trading Scheme (ETS)reduction target is considered in electricity and industry, thus emissions can be pushed from the electricity sector to the supply sector by gasification. Due to the additional reduction which can be achieved already in the electricity sector, industry can still emit more in 2030 in reference scenario. Without any additional push, the reduction until 2050 is also rather limited in industry also because of the additional reduction in electricity.

Residential, agriculture and commercial sectors are able to decarbonize to a certain degree in reference scenario (Figure 13). On the other hand, with a decarbonization target and related efficiency measures and gains (GHG scenario), they can reduce their emissions up to 90% (relative to 2015), the highest level after electricity. With the introduction of the health damage costs in the energy system (GHG_DAM), these sectors benefit in terms of early reductions (2030). In the GHG_DAM scenario, the effort sharing between the sectors to reduce the CO_2 emissions slightly changes. The reduction in the agriculture, commercial and residential sectors slightly decrease mainly due to the limited usage of biomass. On the other hand, with the availability of slightly higher biomass in transport, this sector is able to reduce more compared to the greenhouse gas scenario. As it is used in the form of biodiesel, it has lower specific emissions of air pollutants than in other sectors in which it is mostly utilized in its solid form. In this case, transport can benefit from the integration of health damage costs in form of additional CO_2 reductions.

With the link to NEWAGE, industry further reduces its emission due to reduced demand. Benefitting from this additional reduction, agriculture, residential and commercial emit, on the other hand, slightly more in the IAT scenarios compared to the other scenarios (Figure 13) although, they still reduce their emissions more than industry and transport. Industry still appears to be difficult to decarbonize, only achieving less than 70% reduction in all considered scenarios. Including macro-economic variations (IAT scenarios vs. GHG_DAM) also only helps to further reduce CO_2 emissions in this sector.

Figure 13. Sectoral CO_2 emission reductions relative to 2015 emissions in the EU28 (black squares refer to the relative CO_2 reduction targets according to 2015 level to be achieved in 2030 and 2050).

Transport emissions follow a steadier path across the scenarios compared to other sectors. In 2050, only slight decreases are seen in IAT scenarios again and a slight increase with the introduction of health damage costs. Due to efficiency improvements in the technologies and expected cost reductions in the electric vehicles, emissions can reduce up to 65% compared to their 2015 level, even in the reference scenario. On the other hand, the more ambitious decarbonization target is only able to achieve an 80% reduction (relative to 2015). This makes transport the hardest to decarbonize beyond 80% compared to other non-ETS sectors.

Considering the reduction target defined for the entire energy system, industry benefits form the other sectors and their additional reductions in all scenarios. The electricity sector always carries the greatest burden with the availability of more cost-efficient mitigation options compared to other sectors as seen in Figure 13. According to expected technological developments in transport, earlier reductions are easier to achieve and can also take the burden from the other sectors. On the other hand, in the late periods, it becomes more difficult to push the reductions beyond the targets. Agriculture, commercial and residential benefit from the early reductions especially in transport but with the expected technology development and efficiency measure in these sectors, they can also further reduce their emissions in later periods and can take some of the burden from industry.

3.3.2. Total System—Decomposition Analysis

To identify the role of different mitigation options in the decarbonization of the energy system, CO_2 decomposition analysis is carried out by applying the LMDI method as explained in Section 2.4. According to Equation (5) in Section 2.4., we consider changes in carbon content as an indicator of fuel switching and divide the structural change into two main parts: renewables and nuclear. For the activity change, service demand change is taken into account which is a direct result of the link with NEWAGE, presenting a novelty of our study. Through this link, energy service demands are able to react to the given decarbonization path. The role of energy efficiency improvements is also considered as described in Equation (5).

With the given reduction target, there is a need to reduce the CO_2 emissions by an additional 1.2 Mt in 2050 in the energy system compared to Reference scenario. Figures with the absolute numbers for this analysis can be found in Appendix C.1. The relative contribution of each identified driver is given in Figure 14. In all scenarios, the main mitigation option appears to be renewables. Similarly, fossil fuel switching has the second highest share in all scenarios. This is mainly due to the application of CCS technologies and accounts for at least 20% of CO_2 reductions. Considering that TIMES PanEU is a cost-optimization model, it deploys the cost-efficient technologies in all the scenarios, even in the reference scenario. Hence, the role of energy efficiency improvements is also almost constant across all scenarios. The role of nuclear becomes more important after the introduction of the health damage costs and even more relevant when also considering the impact of economic variations (IAT scenarios). It partly replaces the contribution of fossil-fuel switching, since CCS performs worse with regard to air pollution. Efficiency losses and associated health damage costs increase the relative costs of this technology and give nuclear a competitive advantage. Since the impact of service demands is directly linked to the coupling with NEWAGE, it is only visible in the IAT scenarios. The highest contribution from service demand is seen in the IAT_25 scenario, which has the lowest decoupling factor. According to Figure 14, this mainly impacts the share of renewables. Although renewables still appear as the main driver, the share of renewables in the decomposition reduces after economic variations are introduced in the system. With a higher decoupling factor, the role of service demand reductions diminishes again, since the change in the energy service demands becomes rather moderate as explained in Section 3.2.2. Certain differences can be observed between the regions in EU28 in decomposition analysis. Countries such as the Netherlands, Sweden, Finland, Spain decarbonize their system with the structural change through renewables. In those countries the share of renewables is higher than the EU28 average. The higher share of renewables mainly compensates the role of fossil fuel-switching in those countries. On the other hand, Poland decarbonizes the energy system mainly with fossil fuel switching and energy efficiency applications without increasing drastically the share of renewables as much as the rest of the countries. Countries such as France and United Kingdom are the main reasons for the share of nuclear in the decomposition. Hence, the structural change in different countries is also influenced by their predisposition on specific energy carriers, defined by their societal preferences, renewable potentials and existing energy system. Service-demand change also has different impacts in different countries. Energy service demands in the countries such as Sweden, Finland, Denmark are only slightly affected by the economic variations. Conversely, higher impact from this effect is seen in the countries with bigger economy such as Germany or France.

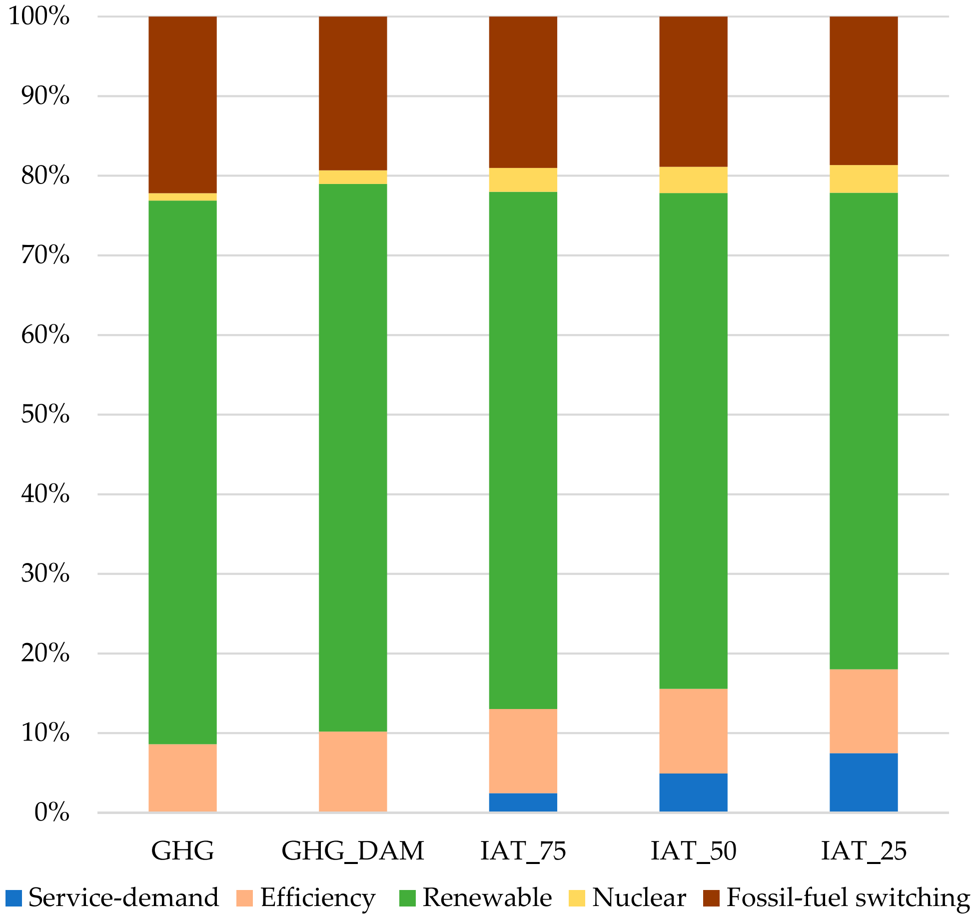

Figure 14. Shares of different mitigation options in CO_2 decomposition analysis compared to reference scenario in different scenarios in the EU28 in 2050.

In summary, taking into account the health damage costs of air pollutants (GHG_DAM scenario compared to GHG) increases the role of efficiency gains, as this equally reduces GHG emissions and air pollutants. Changes in energy service demands will directly affect decarbonization (by reduced demand) and require less contribution from renewables. This also means that neglecting economic variations when determining decarbonization paths may overestimate the role of structural changes and thus the direct costs of the energy transition. The impact of this factor might be even more relevant in end-use sectors and especially in transport, which is typically characterized by high demand and high CO_2 emissions.

3.3.3. Transport CO_2 Emissions—Decomposition Analysis

Considering the sectoral decarbonization rates according to the given reduction target as discussed in Section 3.3.1., transport appears as the most difficult sector between the non-ETS sectors to decarbonize, especially if going beyond 80% compared to 2015 levels. To determine the role of the sector-specific mitigation options during the decarbonization together with the role of service demand changes, we applied a separate decomposition analysis. In contrast to the decomposition of the total system, the structural effect in this analysis is differentiated as biofuels and electricity, since these options are the main technical mitigation options in this sector. Again, figures with absolute numbers for this analysis can be found in Appendix C.2.

Due to the efficiency improvements in the sector and expected cost reductions for electric vehicles, this sector already experiences a high reduction in the reference scenario as mentioned in Section 3.3.1. The main mitigation option to further decarbonize is seen in electricity (more than 60% in all scenarios) as depicted in Figure 15. Although, a high share of electricity is already observed in Reference scenario with the expected cost reduction in electric vehicles, this share additionally increases to achieve the given reduction target in the energy system. Without considering the impact of service demand change (GHG and GHG_DAM), biofuels appear as the second favorite option. With health damage costs in the optimization (GHG_DAM), the role of biofuels increases. As the amount of biomass used in residential sector slightly decreases in residential sector, transport can benefit from the higher availability. Additionally, modern biofuel cars and electric cars both have almost the same emission levels due to road abrasion, tire and brake wear. Yet, biofuel cars still have a cost advantage compared to electric vehicles. This effect is partly compensated for when service demand changes are considered as well.

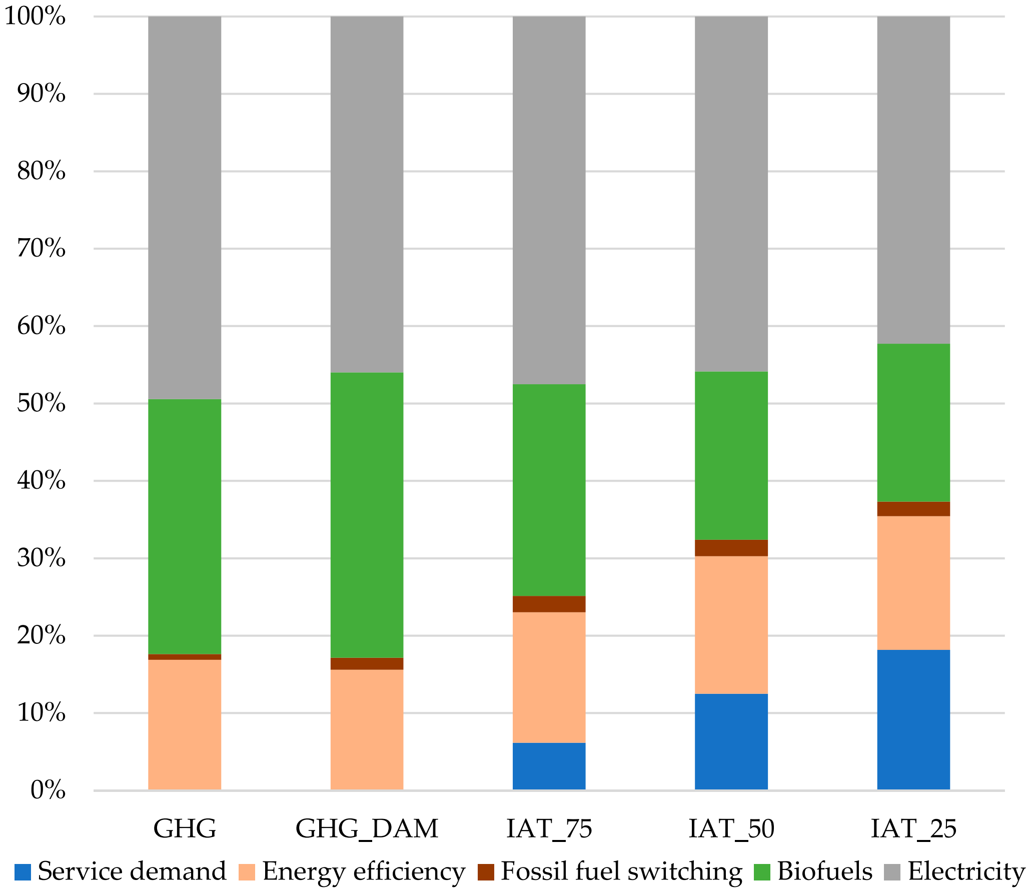

Figure 15. Shares of different mitigation options in CO_2 decomposition analysis in different scenarios in the EU28 in 2050—transport sector.

Service demand changes seem to have a higher impact on the transport decarbonization compared to the overall system (Figures 14 and 15, although private transport is not affected significantly by economic variations (Figure 6, net income effects); the change in public transport accounts for the higher share of service demand changes in the IAT scenarios. With the impact of energy service demand changes, less structural changes are required, reducing the role of biofuels and electricity. This indicates that higher system integration is usually required if the decarbonization path does not account for economic variations. After the link with NEWAGE, the transport sector is also allowed to emit slightly more as explained in Section 3.3.1. Therefore, there is a possibility in these scenarios to utilize a small amount of fossil fuels. With this possibility, navigation utilizes more gasoline by reducing the amount of biodiesel in IAT scenarios compared to GHG and GHG_DAM scenarios. This effect can be seen in Figure 15 with the slightly higher share of fossil-fuel switching.

4. Discussion and Outlook

In this study, we introduced a methodology to create an integrated assessment toolbox to analyze energy transition in the EU considering economic variations and health impacts in the energy system. As a first step in the process, we integrated air pollutants and their health damage costs into the energy system model, TIMES PanEU thanks to the link with Ecosense. We carried out both ex-ante and ex-post analysis. Following, we created the link with a general equilibrium model, NEWAGE. Through this link energy service demands in TIMES PanEU are updated according to their sectoral developments in NEWAGE. In return, the electricity mix in NEWAGE is updated according to TIMES PanEU results. This process is carried out iteratively until the models reach convergence according to the determined convergence criteria. In this process, we also applied a decoupling factor to consider also other variables such as population growth, efficiency gains, comfort and behavioral aspects which also influence energy service demand developments. The objective of this study is to provide and describe a toolbox, which can draw policy relevant insights from the interactions between, the energy system, external effects and economic developments. Therefore, we did not focus on the validation and comparison of alternative models for the individual parts of the integrated toolbox. Instead, the focus is on the toolbox description and demonstrating its potential by providing insights relative to a given reference scenario. Additionally, as this toolbox is first of its kind based on our knowledge so far, the findings are also not directly comparable with the available studies in the literature.

Including health damage cost in the optimization function brings early reductions not only on the health damage costs themselves but also on CO_2 mitigation costs. Simultaneously considering decarbonization targets and air pollutants and their health damage costs, further increases co-benefits. Although the decarbonization target already decreases the level of air pollutants and their health damage costs, internalizing these costs in the energy system accelerates this reduction in the early periods and brings further reductions—also in CO_2 emissions—in the residential sector and industry. The system can benefit from the immediate effects, whereas CO_2 reduction targets rather determine the middle and long term actions. Having such a system also provides insights from the utilization of different energy carriers. Biomass can be given as an example. Although biomass is considered as CO_2 free, having health damage cost in the optimization function can change their utilization in different sectors because of associated emissions of particulate matter. Integration of the health damage costs into the energy system analysis also reduces the total social cost by optimization the both total system cost and health damage costs from the pollutants. In the presented analysis, we only applied country-specific health damage cost factors, ignoring the differences in health impacts of different emission sources. Considering the ongoing discussion about air-quality issues, especially in cities and mainly caused by road transport, further disaggregating health damage costs for different emission sources may affect the effort sharing in GHG reductions between the different sectors. With regard to the different temporal effects of decarbonization targets and health damage costs of air pollution, a different implantation scheme could provide further insights on co-benefits and interactions. As an example, a slower and stepwise introduction of the health damage costs in the system (starting only in 2025, increasing gradually) could reflect a more realistic policy scenario and, in combination with the NEWAGE link, allows us to study the impact of a tax on air pollution in combination with an emission-trading system for GHG.

Energy transition changes the economic variables, such as GDP and sectoral production, and these variables have an impact on the energy-service demands in energy system. Energy service demands, especially in public transportation and industrial branches, are affected after the consideration of these economic variations in the energy system through the link with NEWAGE. This energy service demand change also brings reductions in final and primary energy consumption. As the energy service demands are mainly altered in industry and public transport, final energy consumption of these sectors experience the higher variations compared to other sectors. The impact from the economic variables in the system on the end user sectors such as commercial, agriculture, residential and private transport is limited, since these sectors also react less to the carbon cap and trade system in the macro-economic model. In the case of the commercial and agriculture sectors, they consume less fossil fuels than industrial sectors and are less vulnerable to CO_2 prices. As for residential and private transport, they are matched to utility and net income in NEWAGE, respectively, according to Table A3 and these variables are not affected by the CO_2 prices. For future coupling exercises, it is advised that the sectoral disaggregation of NEWAGE is further refined to better reflect the residential and private transport. With the reduction of renewables in the primary energy consumption, the role of renewables in the decarbonization also slightly diminishes and this is compensated for by the energy service demand change. Integration of economic variables enables the energy transition by also reducing the marginal CO_2 mitigation cost.

To analyze the role of the decoupling factor for the link between NEWAGE and TIMES PanEU, we carried out the iteration process with different decoupling factors. According to our findings, the decoupling factor does not only have an impact on the convergence values of the models but also on the iteration process. Having a decoupling factor of 50% or lower decreases the number of iterations needed to reach convergence but increases the impact on the results. The lower the decoupling factor, the tighter the link between the models. On the other hand, the iteration process took longer with 75% but exchanged data were not changed drastically compared to the reference case. Linking the two models can be a time-intensive task, especially in the early stages of harmonizing assumptions and matching sectors, but it also demands transparency from the modelers, which increases confidence in the entire process. After the required set-up, the linking process becomes also rather straightforward. Therefore, it can be applied in scenario analyses directly without increasing the complexity.

In our study, we did not develop any methodology to determine the decoupling factor but carried out sensitivity analyses to investigate the impacts. We suggest that a more elaborative method could be developed to determine such a factor as it has impacts on the results. Additionally, we believe that a link between the general equilibrium model and the impact assessment model can be considered for further research, which would allow for the analysis of health damage costs directly related to economic variations. Deeper coupling between NEWAGE and TIMES PanEU could be also possible by implementing more data from TIMES PanEU results as input to NEWAGE. The data exchange between the models can be also further elaborated in further research.

As NEWAGE is a global model and TIMES PanEU is a EU model, scenario assumptions are determined at the EU and global level. To determine the EU assumptions, the reduction target is set based on the discussed targets in [1], yet, at the time of this study, no global commitment to decarbonization existed. As trade between the regions is allowed in NEWAGE and decarbonization in one region might affect the dynamics in other regions, the assumptions for the rest of the world might affect the results in the EU. Therefore, a similar study with different global assumptions should be undertaken to assess the impact of different global assumptions. Additionally, we carried out this analysis at the EU level and did not focus on the individual member states. It might be possible to conclude different findings when the role of the demand change and externalities are considered in the energy system for the individual member states instead.

To investigate the role of different mitigation options together with the demand change, CO_2 decomposition analysis was carried out for the whole system. Before this analysis, we also analyzed the sectoral CO_2 reduction paths in each scenario. With the integration of health damage costs in the energy system, effort sharing between residential, commercial, agriculture and transport sectors slightly changed. Transport could reduce slightly more while the others slightly increase their emissions. The role of effort-sharing between the sectors is also observed after the integration of demand change. Due to higher reductions in industry; agriculture, commercial and agriculture could emit more. An increased share of renewables dominates but this share slightly reduces after the integration of service demand change in the decomposition analysis. In our study, the service-demand change is provided with the link of a general equilibrium model as an additional improvement to the existing literature. Integration of economic variables helps to reduce the structural change in the energy system through the energy transition. According to the remaining CO_2 emissions, transport is identified as hardest to decarbonize between the non-ETS sectors. To also investigate the sector dynamics, decomposition analysis is also carried out specifically in the transport sector. Service demand change has a higher impact after the integration of macro-economic variables compared to the overall system in this sector and the main mitigation options appear to be biofuels and electricity. We also suggest as further research analyzing the role of the specific mitigation options in each sector by carrying out decomposition analysis. As the uncertainty also appears with the cost of the mitigation technologies and availability of the sources, further analysis should also address the impact of such uncertainties. Furthermore, different EU countries may prioritize different mitigation options to decarbonize their system based on their existing energy system. It is also seen in our analysis that some of the countries prefer to deploy more renewables, while others favor sticking with fossil fuels by applying options to reduce their carbon-content such as CCS. Therefore, as a further research, we suggest also investigating decomposition analysis at the Member States level to gain more insights for the further development of their energy system during the energy transition.

Based on our analysis, implementing the economic variations and health damage costs and considering these in scenario construction determines different CO_2 reduction paths as it is seen in the decomposition analysis. Instead of the isolated energy system, it will also be important to take into account these elements outside the energy system during the energy transition. With this analysis, we showed a more complete picture of the energy transition together with these elements. Reducing GHG emissions does not only affect the system itself but the whole economy and society. A comprehensive analysis including economic variations and impacts on society in the form of reduced health costs allows us to account for co-benefits and interactions with economic mechanisms such as a carbon cap and trade system. This integrated view can provide valuable insights to determine efficient and effective decarbonization paths as well as increase awareness of interactions and side effects, which may help to increase acceptance of specific, necessary changes.

Author Contributions: Conceptualization, P.K., R.C.M., D.S. and U.F.; Methodology, P.K., R.C.M. and D.S.; Formal analysis, P.K., R.C.M. and D.S.; Investigation, P.K. and R.C.M.; writing—original draft preparation, P.K. and R.C.M.; Writing—review and editing, P.K., R.C.M., D.S., U.F. and M.B.; visualization, P.K. and R.C.M.; supervision, P.K., R.C.M., M.B. and U.F.; Project administration, U.F. All authors have read and agreed to the published version of the manuscript.

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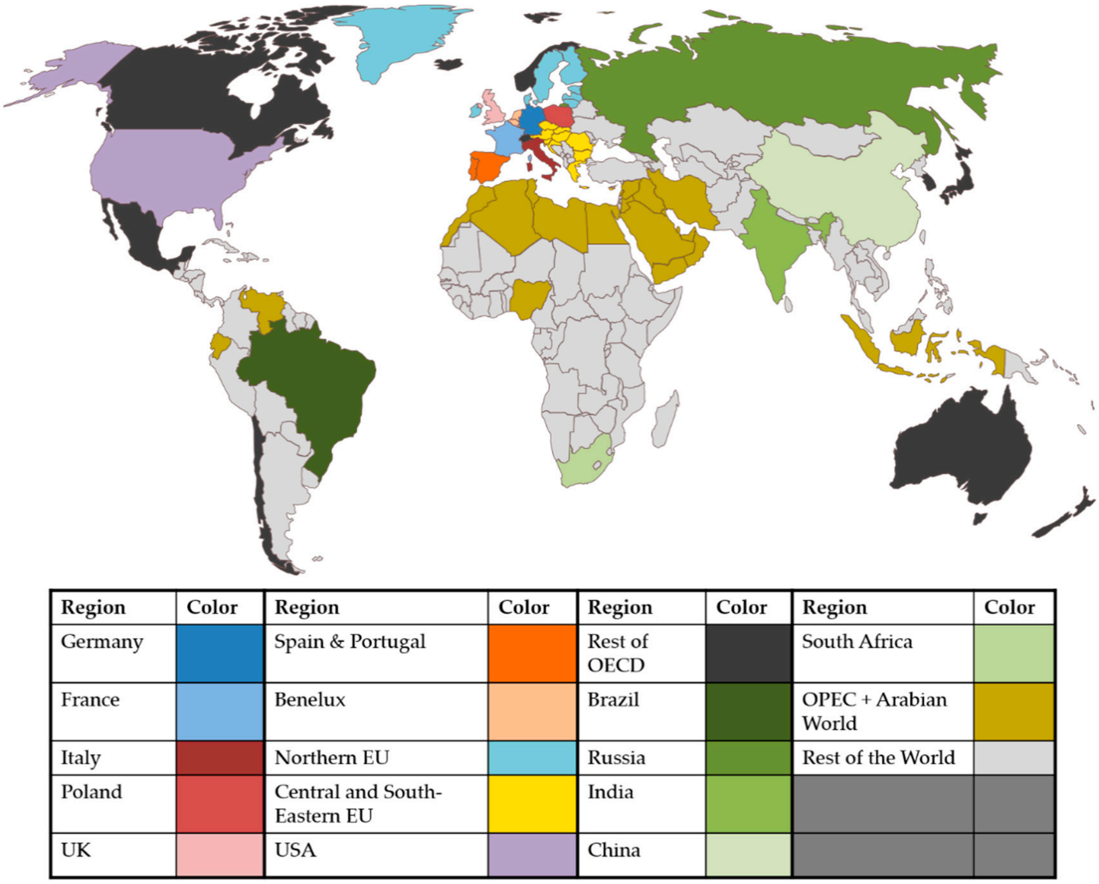
Appendix A



Region	Color	Region	Color	Region	Color	Region	Color
Germany	🟦	Spain & Portugal	🟧	Rest of OECD	⬛	South Africa	🟩
France	🟦	Benelux	🟧	Brazil	🟩	OPEC + Arabian World	🟨
Italy	🟥	Northern EU	🟦	Russia	🟩	Rest of the World	⬜
Poland	🟥	Central and South-Eastern EU	🟨	India	🟩		
UK	🟥	USA	🟪	China	🟩		

Figure A1. Regional disaggregation in NEWAGE. Each region in the model has its own color in the map.

Table A1. List of production sectors in NEWAGE.

No.	Sector	Group
1	Coal	Energy production
2	Natural gas	Energy production
3	Crude oil	Energy production
4	Oil refining	Energy production
5	Electricity	Energy production
6	Iron and Steel	Energy intensive industries
7	Non-ferrous metals	Energy intensive industries
8	Non-metallic minerals	Energy intensive industries
9	Paper, pulp and print	Energy intensive industries
10	Chemicals	Energy intensive industries
11	Food and Tobacco	Energy intensive industries
12	Motor vehicles	Other manufacturing
13	Machinery	Other manufacturing
14	Rest of industry	Other manufacturing
15	Buildings	Rest of the economy
16	Transport	Rest of the economy
17	Agriculture	Rest of the economy
18	Services	Rest of the economy

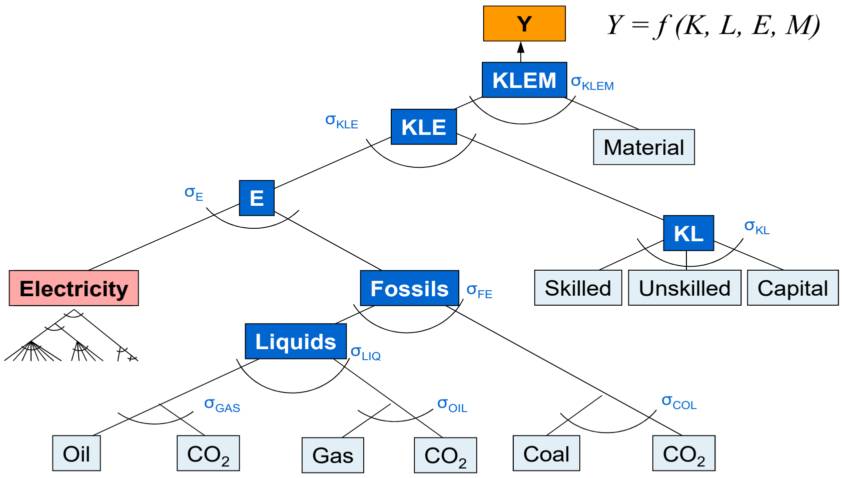


Figure A2. CES structure in NEWAGE for the production sectors.

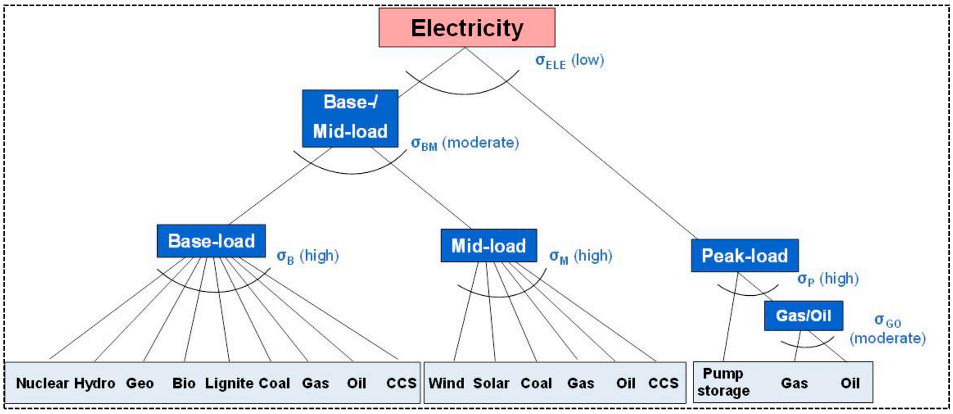


Figure A3. CES structure in NEWAGE for electricity production.

Regional Push

The regional push scenario can be translated as the mutual work of several regions that, together, concentrate at least half of the global emissions and have the economic means to pursue emission targets that are consistent with the 2 °C target, according to the 2DS path presented in [39], or at least more ambitious than the current policies, as shown in the RTS path presented in [39].

Since the EU-28 has specific emission targets, Table A2 depicts only the emission targets of NEWAGE's regions outside of the EU that pursue a higher emission cut than the current policies in the Regional Push World state.

Table A2. Emission targets for regions outside of the EU-28 pursuing emission cuts higher than the current policies for the regional push world state.

Region	CO_2 Emission Targets in 2050
USA	Halfway between 2 °C target and current policies
China	2 °C target
Japan	Halfway between 2 °C target and current policies
Republic of Korea	2 °C target
Canada	Halfway between 2 °C target and current policies
Mexico	Halfway between 2 °C target and current policies
Australia	Halfway between 2 °C target and current policies
Norway	80% reduction compared to 1990 levels
Switzerland	80% reduction compared to 1990 levels
New Zealand	2 °C target
Iceland	2 °C target

Appendix B

Table A3. The sectoral match between TIMES PanEU and NEWAGE.

TIMES PanEU	NEWAGE
AGR	Agriculture
Commercial Cooling large	Services
Commercial Cooking	Services
Commercial Cooling small	Services
Commercial Heating large	Services
Commercial Heating small	Services
Commercial Lighting	Services
Commercial Other electricity	Services
Commercial Other energy	Services
Commercial Public lighting	Services
Commercial Refrigeration	Services
Commercial Water heat large	Services
Commercial Water heat small	Services
Aluminum	Non-ferrous metal
Ammonia	Chemistry
Other chemical	Chemistry
Chlorine	Chemistry
Cement	Non-metallic minerals
Copper	Non-ferrous metal
Food and Tobacco	Food and Tobacco
Glass Flat	Non-metallic minerals
Glass Hollow	Non-metallic minerals
Iron and Steel	Iron and Steel
Lime	Non-metallic minerals
Other non-ferrous metals	Non-ferrous metal
Other non-metallic minerals	Non-metallic minerals
Other industries	Rest of Industry
High-Quality paper	Paper Pulp Print
Non energy-consumption chemicals	Chemistry
Non energy-consumption others	Non-metallic minerals
Other Sector Consumption	Services
Other electricity	GDP
Road Transport (Short- Long-Distance)	Net Income
Motorcycle	Net Income
Bus/Train (Public Transport)	Transport
Truck (Freight)	Transport
Rail Freight	Transport
Aviation (Internal/External)	Transport
Navigation (Internal/External)	Navigation
Residential Space Heating Multi, Urban, Rural	Utility
Residential Space Cooling Multi, Urban, Rural	Utility
Residential Water Heat	Utility
Residential Cooking	Utility
Residential Cloth Washing and Drying	Utility
Residential Lighting	Utility

Table A4. Electricity technology match NEWAGE and TIMES PanEU.

NEWAGE		TIMES-PanEU Technologies
Technology	Load	Technology
Nuclear	Base	Nuclear
Hydro	Base	Run of River
	Peak	Dam Storage; Pump Storage
Geothermal	Base	Geothermal
Solar	Medium	Solar
Wind	Medium	Wind
Hard Coal	Base	Coal—Steam Turbine (CHP)
	Medium	Coal—Steam Turbine (not CHP)
Lignite	Base	Lignite—Steam turbine
Oil Products	Base	Oil—Combined Cycle
	Medium	Oil—Gas Turbine
	Peak	Oil—Internal Combustion; Steam Turbine
Natural Gas	Base	Natural Gas—Combined Cycle
	Medium	Natural Gas—Gas Turbine
	Peak	Natural Gas—Steam Turbine; Internal Combustion

Table A4. *Cont.*

NEWAGE		TIMES-PanEU Technologies
Biomass	Base	Waste non-renewable; Biomass solid/Waste ren.; Biogas/Biofuel
CCS	Base	CCS from Lignite
	Medium	CCS from Hardcoal

Appendix C

Appendix C.1 Total System—CO$_2$ Decomposition Analysis

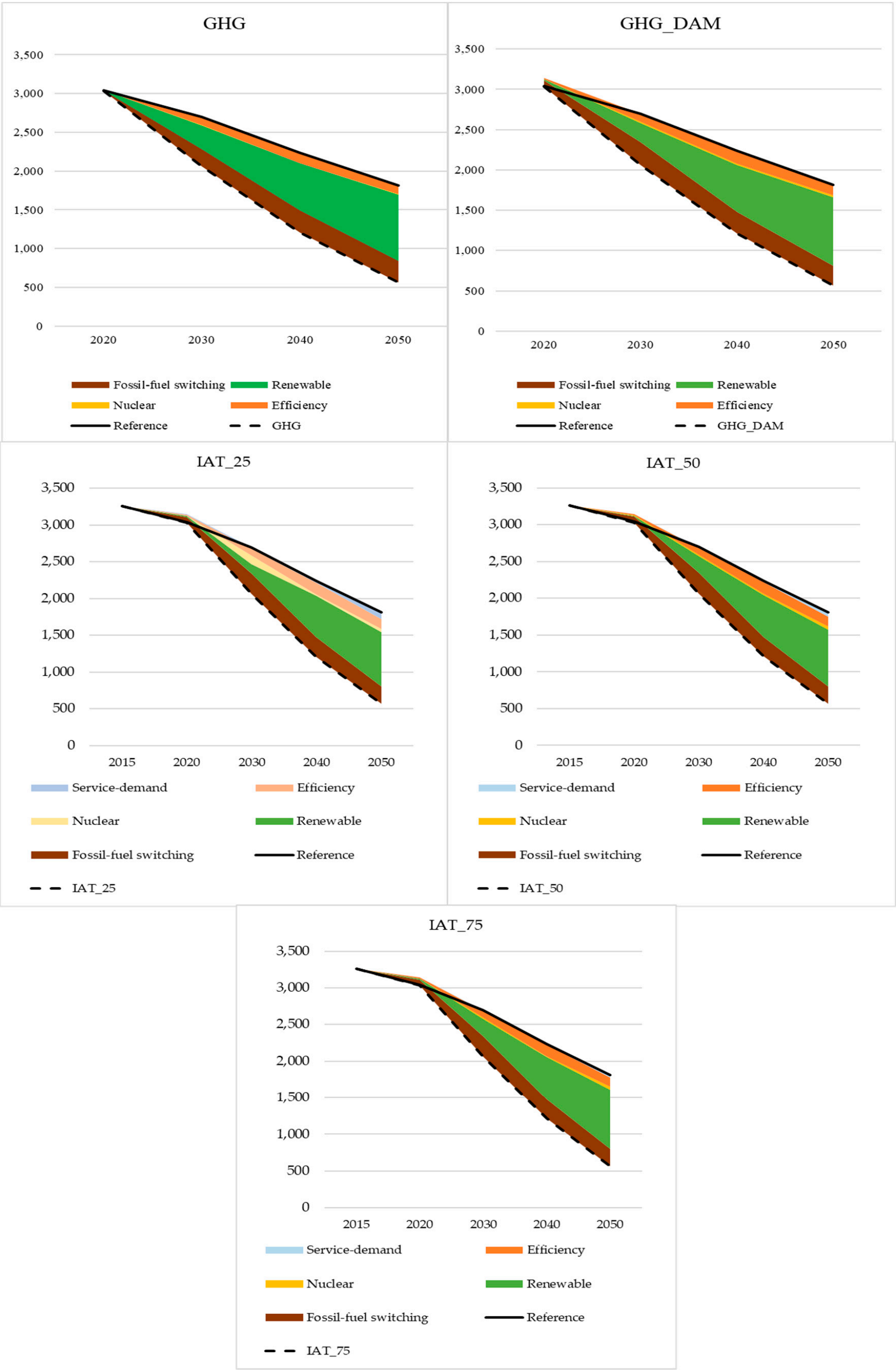


Figure A4. CO$_2$ Decomposition (Mt)—total system in the EU28.

Appendix C.2 Transport—CO_2 Decomposition Analysis

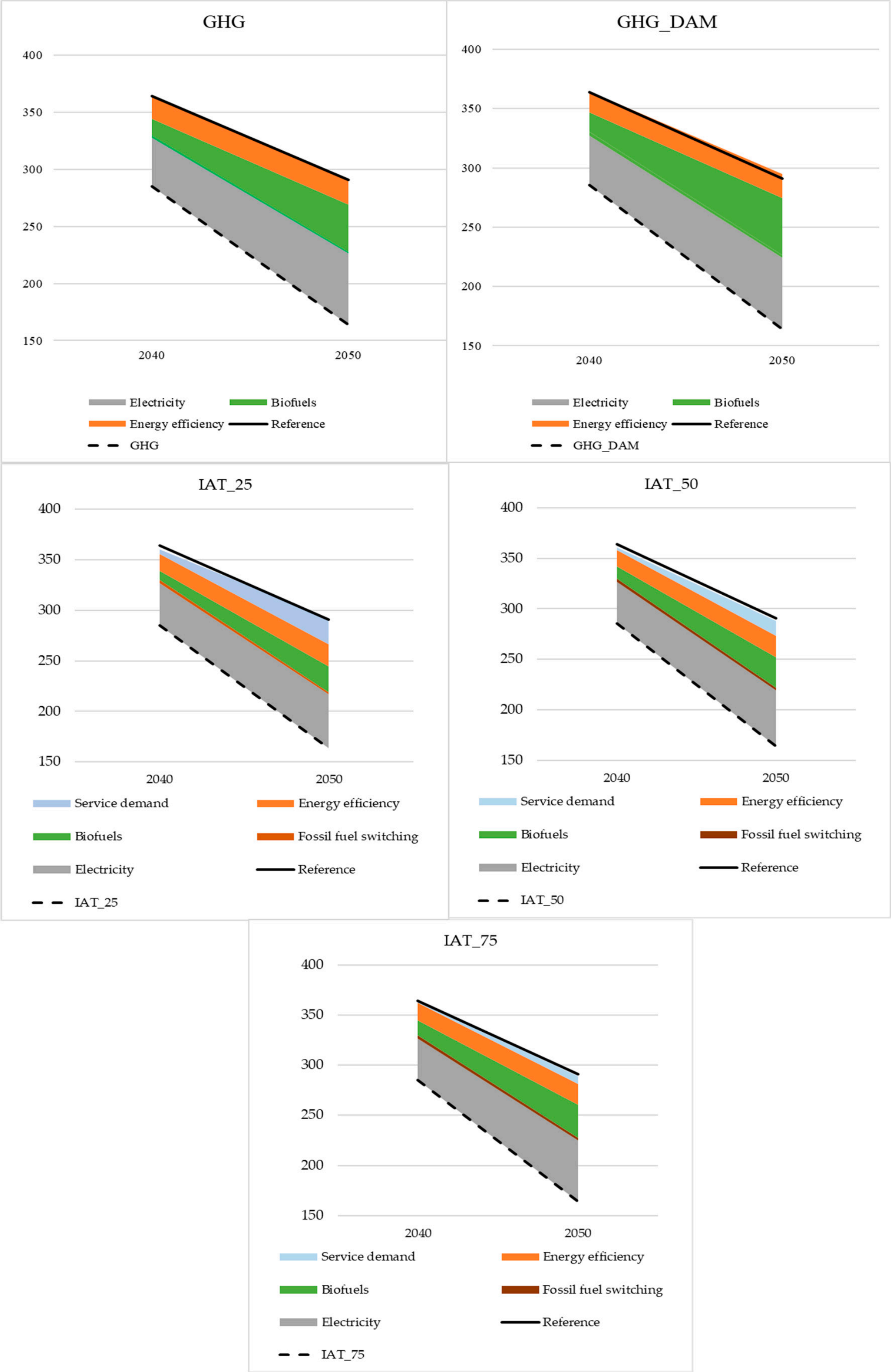


Figure A5. CO_2 decomposition (Mt)—transport in the EU-28.

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3.2 Publication II

Analyzing transformation pathways to a sustainable European energy system - Internalization of health damage costs caused by air pollution

Authors: Dorothea Schmid, Pinar Korkmaz, Markus Blesl, Ulrich Fahl, Rainer Friedrich

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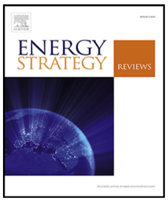

Analysis

Analyzing transformation pathways to a sustainable European energy system—Internalization of health damage costs caused by air pollution

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Keywords:
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ABSTRACT

On its way to a low-carbon society, various transformation pathways for the European energy system are possible. Additionally, improving air quality may benefit from or influence climate change mitigation. In a comparative scenario analysis, interactions between decarbonization targets and air pollution control as well as their implications on the European energy system are studied. For this purpose, the European energy system model *TIMES PanEU* is linked with the impact assessment model *EcoSense* to internalize the health costs related to air pollution. Results indicate that ambitious GHG reduction targets are most influential with respect to system transformations. Internalizing health impacts leads to welfare savings by reducing air pollution while still achieving the given reduction targets with lower utilization of carbon capture and storage as well as biomass. Especially the latter may partially be contradictory to targets on the share of renewable energy sources. Hence, integrated policies tackling climate change and air pollution alike may foster the transition to a low-carbon society. To gain a better understanding of the interplay between reduction targets, the share of renewable energy sources, and air pollution control, further research studying sector- and country-specific impacts in more detail is still needed.

1. Introduction

In line with the Paris Agreement, the EU envisions a competitive, low-carbon society by 2050, requiring ambitious reductions in greenhouse gas (GHG) emissions [1]. Decarbonization can thereby follow different pathways, resulting in different costs and impacts. In addition, the EU struggles with air quality and strives to reduce related health impacts [2]. With most emissions of air pollutants being energy-related [3], air pollution control interacts directly with climate change mitigation, especially regarding the energy system transformation. Since both GHG and air pollutants arise mainly from burning fossil fuels, reducing GHG emissions usually facilitates reductions in air pollution. Such mutual benefits can partly compensate for GHG mitigation costs. Hence, air pollution control may increase incentives for climate change mitigation [4,5]. At the same time, both GHG mitigation and air pollution control drive changes in the energy system which may foster or hamper each other in achieving clean air and a low-carbon society.

Building upon previous research [6–9], this study employs the concept of external costs of air pollution in combination with ambitious GHG reduction targets in 2050 to investigate possible interactions between air pollution control and decarbonization targets in the European energy system. In contrast to previous studies, which focused either only on one country or parts of the energy system such as electricity production, the full energy system is considered on a European level, following the idea of an Energy Union. For this purpose, the impact assessment model *EcoSense* is linked with the European energy system model *TIMES PanEU*, which is run for different sets of decarbonization pathways. In a comparative scenario analysis, the changes in the European energy system due to the costs of air pollution on top of ambitious and binding GHG reduction targets are identified and discussed. The focus of this analysis is on the EU28 level, taking an integrated perspective on the European energy system in line with the Energy Union approach.

The paper is outlined as follows:

First, the applied models and underlying methodology are explained in Section 2. Section 3 elaborates on the main assumptions and differences between the studied scenarios. A comparative analysis of these scenarios is then carried out in Section 4. The focus is hereby on changes in the power sector and in final energy consumption as relevant indicators for energy system transformations. Effects on the costs of air pollution are also discussed to identify possible gains in welfare. Finally, key messages, limitations, and implications for further research are presented in Section 5.

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2. Methodology

2.1. Study design

To enable an integrated analysis of air pollution control and decarbonization in the energy system, external effects of air pollution need to be reflected in an energy system analysis. By definition, external costs arise, when economic transactions have negative impacts on an uninvolved third party, which leads to a loss in welfare. In the case of air pollution, emissions of local air pollutants such as particulate matter cause environmental damages and adverse health effects. If monetized, the respective damage costs reflect the monetary loss in welfare [10]. To account for the negative impacts of air pollution, these costs should be considered as part of the optimization function in an energy system model. The optimal solution then shifts from a merely economic optimum to a rather social optimum in the sense of welfare maximization, efficiently avoiding external effects as long as their avoidance cost do not exceed their damage cost. By linking the energy system model *TIMES PanEU* and the impact assessment model *EcoSense*, it is possible to estimate marginal health damage costs per pollutant, which can, in turn, be directly included in *TIMES PanEU* as an additional cost parameter on emission streams. To gain a better understanding of the chosen approach, the two models are briefly described hereafter, before the link itself is explained.

2.2. *The energy system model* TIMES PanEU

The Pan-European TIMES energy system model (*TIMES PanEU*) is built with the TIMES model generator [11], developed and maintained within the *Energy Technology System Analyses Program (ETSAP)* of the International Energy Agency (IEA) to facilitate policy and scenario analysis based on technical-economic energy system models. *TIMES PanEU* is a bottom-up linear partial equilibrium model reflecting the entire European energy system with a time horizon from 2010 up to 2050. It minimizes discounted energy system costs according to exogenously projected energy service demands (e.g. person-kilometer, heat demand for residential buildings), energy technologies, and policy requirements based on five-year intervals; each interval is represented by a milestone year [11,12]. *TIMES PanEU* covers all European Union member states as well as Norway and Switzerland. Each country is modeled as a single region including electricity and resource trading. The reference energy system of the model represents all energy, material, and emission flows across the entire energy system, starting from the supply of resources (primary production) and ending with fulfilling different energy service demands for each defined region. It is split into seven main sectors (supply, electricity and heat production, industry, commercial, residential, agriculture, and transport) reflecting different demand structures and transformation steps. All sectors can interact with each other and different indicators (e.g. energy use) are calculated through each step in the reference system. For the years 2010 and 2015, energy balances (primary and final energy consumption as well as installed capacities) are calibrated to statistics. For future years, the model can choose to deploy different technologies in each sector to meet the given energy services in a cost-efficient way. Typically, these technologies are characterized by their fuel type, efficiency, availability, lifetime, and cost structure (incl. investment costs, fixed costs, and variable costs). To be able to analyze environmental policies, GHG (CO_2, CH_4, N_2O) and local air pollutants ($PM_{2.5}$, PM_{10}, NO_X, SO_2, NH_3, NMVOC, CO) are also included in the model [13–17]. Available technologies in *TIMES PanEU* include conventional and advanced technologies using fossil fuels (e.g. coal power plants, gas boiler) or renewable energy sources (e.g. hydropower plant, PV panels or biomass), storages (electricity and heat), hydrogen technologies, electrification (e.g. road transport) and carbon capture and storage (CCS, fossil fuels only). Availability of new technologies like CCS, heat pumps or electric vehicles is determined according to their expected schedule to become commercially available in the market. Assumptions for storage technologies, for example, follow the *REEEM Innovation and Technology Roadmap* [18]. Regarding energy efficiency gains, the model can either choose new technologies with higher efficiencies (e.g. new cars, more efficient production technologies) or invest in explicitly modeled saving measures (e.g. advanced isolation of buildings) which directly reduce energy service demands at a specific cost. In addition, existing energy efficiency standards such as for new buildings are also reflected in the applied energy service demand projections. All relevant input parameters including technology characterization factors, cost components, and energy service demands will be published in the REEEM project database.[1]

2.3. *The impact assessment model* EcoSense

EcoSense is an impact assessment model to simulate and estimate health and environmental impacts caused by different air pollutants. Its main focus is to assess net benefits of air pollution mitigation scenarios across Europe with a time horizon up to 2050. The model implements the *Impact Pathway Approach* developed within the ExternE project series [19], linking changes in emissions of several air pollutants to different health outcomes by integrating atmospheric modeling with epidemiological studies and economic assessment of impacts [10, 20,21]. To account for long-range transport of emissions and their chemical transformations at reasonable computation time, *EcoSense* implements a parameterized atmospheric dispersion model based on the EMEP/MSC-W model [22,23]. Changes in emissions of SO_2, NO_X, NMVOC, NH_3 and primary particles ($PM_{2.5}$ and PM_{10}) in a given country are allocated to changes in concentration levels of Ozone, NO_2 and particulate matter (separated in $PM_{2.5}$ and PM_{10}, incl. primary and secondary particles) across Europe and neighboring regions in Africa and Asia on a $0.5° \times 0.25°$ grid. By applying concentration–response-functions for short and long-term exposure to ambient air pollution as recommended by the World Health Organization (WHO) [24], different health outcomes are estimated, inter alia increased mortality, hospital admission and work days lost. Concentration–response functions state the increase in relative risk of a specific outcome due to a defined increase in ambient air concentration levels. Combined with detailed population data and background disease rates as recommended by [24] and [25], additional cases due to the original changes in emissions can thus be calculated. The population data in *EcoSense* combines the spatial distribution of the high-resolution population density grid for Europe [26] with UN data on country-specific age structures and population projections. The different health impacts are summed up in monetary values by applying specific health cost factors for each health outcome. For impacts on mortality, a willingness-to-pay approach (“Value of Life Year”) is adopted. Other impacts (e.g. hospital admissions) are monetized based on a standard price approach. All monetary values used in *EcoSense* are based on the HEIMTSA/INTARESE case study [20]; for health outcomes not part of HEIMTSA/INTARESE (e.g. bronchitic symptoms), monetary values given in [25] are adopted.

2.4. *Integrating local externalities in* TIMES PanEU

If local externalities are included in *TIMES PanEU* as additional costs, the model setup provides a switch to explicitly in- or exclude these costs in the optimization. This allows to directly study the impact of these additional costs and thus of air pollution control on the energy system in a comparative scenario analysis. For the technical description of how these cost factors are implemented and treated in *TIMES* models,

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[1] The REEEM project database will be made publicly available as part of the REEEM project (reeem.org). To request access, please contact the corresponding author.

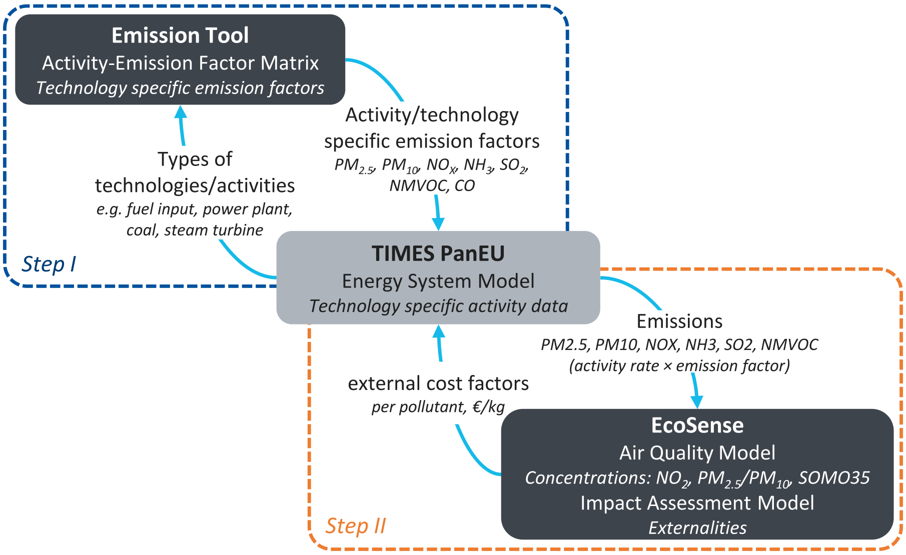

Fig. 1. Link between the energy system model *TIMES PanEU* and the impact assessment model *EcoSense*.

please refer to [7,8,27]. This section focuses on the link between the two models applied in this study to integrate marginal damage costs as calculated by *EcoSense* in *TIMES PanEU*. The link and data exchange between the models is depicted in Fig. 1.

In a first step, emission factors of local air pollutants in *TIMES PanEU* are updated to reflect future emission standards in line with current EU legislation [2] and expected penetration of technical mitigation options (e.g. filters and catalyst). Whenever possible, technology-specific emission factors are used and applied on process level in *TIMES PanEU*. If technology specific emission factors are not available, sector and fuel specific factors, which reflect average conditions with regard to air pollution control, are used instead. This means that different processes in *TIMES PanEU* may have the same emission factor; emission streams are calibrated on sector and fuel level. All emission factors except for railway and road transport are based on the *Eclipse V5a Scenario* [28]. This scenario reflects policy assumptions and data of the latest revisions of the *National Emission Ceilings* in Europe [29, 30]. Hence, future emission factors represent the *Industrial Emissions Directive* [31], including the requirement for industrial processes to follow the best available techniques. A comprehensive list of considered emission control policies can be found in [32]. As these regulations also focus on primary particles, NO_X, SO_2, NH_3 and NMVOC as the main air pollutants affecting human health, it is decided to concentrate on these substances with regard to marginal damage costs in this study. Emission factors are either applied to the amount of fuel consumed (combustion processes) or on the quantity of product produced (process emissions). For railway and road transport, emission factors are implemented based on driven vehicle kilometers; this approach allows to integrate primary particles due to abrasion and tire/brake wear. In addition, NMVOC emissions from evaporation processes are included. For road transport, all emission factors are taken from the *COPERT 5* [33] model to also reflect the influence of driving conditions. Since *TIMES PanEU* does not differentiate activities according to vehicle emission standards, average emission factors based on national fleet mixes as given by the *TREMOVE 3.3.2* [34] model are applied for base-year technologies. For new technologies, the appropriate emission standard is used, i.e. EURO 6 for all new cars in 2015; from 2020 on all new cars receive emission factors following EURO 6d. Emission factors for railways are based on the EMEP/EEA Guidebook [35].

By running *TIMES PanEU* once, emission streams for each country are obtained, which are fed to *EcoSense*. *EcoSense* is then run separately for each pollutant, country and year to estimate annual, pollutant- and country-specific marginal damage costs, assuming that:

- Damages occurring in one year only relate to the emissions released in this year, i.e. there is no time lag between cause and impact. By that, only additional impacts occurring in a specific year are attributed to specific changes in emissions. This enables estimating annual marginal costs.
- Damages are allocated according to the Polluter Pays Principle, i.e. all damages across Europe caused by emissions of one country are allocated to this country.
- All impacts are additive, i.e. total damages are the sum of all pollutant-specific damages [36], with impacts due to $PM_{2.5}$ and PM_{10} relating to different health outcomes (e.g. chronic mortality vs. bronchitic symptoms). With regard to possible cross-impacts on mortality due to $PM_{2.5}$ and NO_2 [24], only 66% of this impact category is considered for NO_2.
- As recommended by the WHO for cost benefit analysis, all concentration–response functions are considered to be linear [24, 25]. Recent research indicates that not all concentration–response functions may be linear [37,38]. Yet, these findings only refer to particulate matter and cause-specific mortality on a global scale; their implications for cost benefit analysis on European level still need to be evaluated.
- In line with recent research and the use of a parameterized dispersion model, the influence of possible non-linearities on annual mean values due to chemical transformations of pollutants is assumed to be negligible [23,39].
- Since we are interested in marginal damage costs, no lower threshold level is assumed in the concentration–response functions except for mortality impacts due to NO_2. Here, a threshold of $20\,\mu g/m^3$ is assumed as recommended by [24,25].

In line with these assumptions, all cost factors are calculated as $€_{2010}/kg$ and implemented as linear cost functions with respect to the level of emissions released. Since current health costs due to air pollution are not yet internalized, the marginal cost factors are only implemented in the energy system model from 2020 on. To also account for the five-year model structure, with 2020 being representative for the period 2018–2022, the applied unit cost factors for 2020 only correspond to half of the marginal damage costs. From 2030 on, the applied cost factors correspond to the actual marginal damage costs. However, this still means that the costs calculated with *TIMES PanEU* by multiplying annual emission streams with their respective cost factors do not reflect the actual damages over the complete time horizon. For the current study, these cost factors are also implemented as scenario-independent.

Table 1
Unit cost factors of air pollutants as implemented in *TIMES PanEU* based on results from *EcoSense*.

	Unit cost factors in €$_{2010}$/kg (mean value [min; max])			
	2020	2030	2040	2050
NH_3	8.62 [1.41;22.13]	17.26 [2.95;44.18]	16.92 [3.02;42.79]	16.57 [3.09;41.41]
NMVOC	1.19 [0.31; 2.86]	2.39 [0.64; 5.61]	2.35 [0.63; 5.61]	2.31 [0.63; 5.51]
NO_X	4.48 [0.55;10.72]	8.98 [1.10;21.63]	8.83 [1.09;21.29]	8.68 [1.08;20.94]
$PM_{2.5}$	25.94 [3.99;48.88]	52.13 [8.03;99.35]	51.26 [7.94;97.70]	50.39 [7.84;96.04]
PM_{10}	0.90 [0.14; 1.97]	1.80 [0.28; 3.99]	1.78 [0.28; 4.01]	1.77 [0.28; 4.01]
SO_2	10.54 [2.20;28.14]	21.19 [4.43;56.92]	20.85 [4.37;56.00]	20.51 [4.30;55.08]

Table 1 contains the mean unit costs per pollutant as well as the observed minimum and maximum values reflecting the span of costs across countries and pollutants. The full dataset of country and pollutant specific unit cost factors from *EcoSense* will be published in the REEEM project database.[2] The highest values are observed for $PM_{2.5}$ and SO_2 (forming secondary aerosols), both being a major source of impacts on mortality. The high variance between the different countries relates to differences in the exposed population. Emissions from small islands such as Cyprus or Malta do not affect as many people as emissions from highly populated countries in central Europe, e.g. Germany. Due to this spatial variance, only country-specific cost factors can thus reflect the Polluter Pays Principle.

3. Scenario assumptions

This study considers two distinct transformation pathways towards a European low-carbon society as developed within the EU Horizon 2020 project REEEM. The pathways provide a consistent description of a possible future, decarbonization targets and further technological, social and environmental developments [40,41]. Both pathways are placed within the same possible future which corresponds to the “Those Who Want More Do More” scenario as discussed in the ‘White paper on the future of Europe’ at the State of the Union 2017 [42]. Energy policies within the EU will have more parallels within clusters of member states, with some countries setting more ambitious targets than others. As described in [40], countries are clustered based on their socioeconomic situation, availability of resources and their geographical location. The underlying assumptions with respect to socioeconomic developments and demand projections are in line with the *EU Reference Scenario* [43] and the electricity grid follows the 10-year network development plan [44].

On both pathways, *TIMES PanEU* is run two times — with and without including health impacts of local air pollutants and their respective costs in the optimization. Hence, four scenarios are analyzed in total. Table 2 summarizes their main assumptions and differences.

Table 2
Main assumptions and differences between the calculated scenarios.

Policy	Scenario acronym			
	Base	Base_DAM	HighRES	HighRES_DAM
GHG ETS[a]	2020 Climate and Energy Package 2030 Climate and Energy Framework 2050: −83% GHG			
GHG non-ETS	Effort Sharing Decision/Regulation 2050: country clusters[b]			
RES	-		Renewable Energy Directive 2050: country clusters[c]	
Health impacts	ex-post	ex-ante	ex-post	ex-ante

[a] GHG reduction relative to 2005 levels in ETS sectors on EU28 level.
[b] Aiming at 75% GHG reduction in EU28 in non-ETS sectors, relative to 2005 levels.
[c] Aiming at a share of 75% of RES in EU28.

Table 3
Considered country clusters with their respective non-ETS GHG and RES targets.

Country cluster	GHG non-ETS (2050 rel. to 2005)	RES (2050)
Austria, France, Italy, Portugal, Spain, United Kingdom	−80%	85%
Belgium, Germany, Luxembourg, Netherlands	−80%	65%
Denmark, Finland, Ireland, Sweden	−80%	85%
Czech Republic, Poland	−50%	45%
Bulgaria, Croatia, Cyprus, Estonia, Greece, Hungary, Latvia, Lithuania, Malta, Romania, Slovakia, Slovenia	−60%	75%

In line with the anticipated future as described above and in [40, 41], the *Base* pathway takes into account all existing EU-wide GHG-reduction goals as set in the *2020 Climate and Energy Package* [45] and the *2030 Climate and Energy Framework* [46]. Accordingly, in 2020 a 20% reduction and in 2030 a 43% reduction compared to 2005 levels are implemented as constraints for all GHG emissions under the *EU Emissions Trading System* (ETS) [47]. For non-ETS GHG emissions, the implemented reduction targets in 2020 and 2030 reflect country-specific reduction levels according to the binding effort sharing decisions [45,48]. The implemented reduction targets for 2050 are chosen in line with the *Energy Roadmap 2050* [49], leading to an EU-wide 83% reduction of GHG emissions compared to 2005 levels for the ETS. For non-ETS GHG emissions, the concept of effort sharing is applied to the defined country clusters leading to an EU-wide reduction of 75% relative to 2005 levels in 2050. As this study aims to analyze interactions between air pollution control and decarbonization, both pathways follow the same ambitious decarbonization targets with the alternative *HighRES* pathway implementing additional targets for the share of renewable energy sources in gross final energy consumption (RES). For 2020 and 2030, these national targets follow the *Renewable Energy Directives* [50,51]. Targets in 2050 are again chosen according to the defined country clusters to match a 75% share across the EU as laid out in the *Energy Roadmap 2050* [49]. The resulting 2050 targets for the chosen country clusters for both GHG reduction and RES are stated in Table 3. A full list of all country-specific targets over the years is given in [40].

4. Results

4.1. System transformation and decarbonization

4.1.1. Final energy consumption

When it comes to final energy consumption as the first main indicator for decarbonization in the energy system, all scenarios show a continuous decline in fossil fuel use in EU-28 until 2050 as depicted in Fig. 2. In contrast, the shares of electricity and renewable energy sources grow steadily over time. As it is more cost-efficient to reduce GHG emissions in the electricity production than in other sectors, electrification plays a key role in achieving the targets. Even without explicitly modeled constraints on the share of renewable energy

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[2] The REEEM project database will be made publicly available as part of the REEEM project (reeem.org). To request access, please contact the corresponding author.

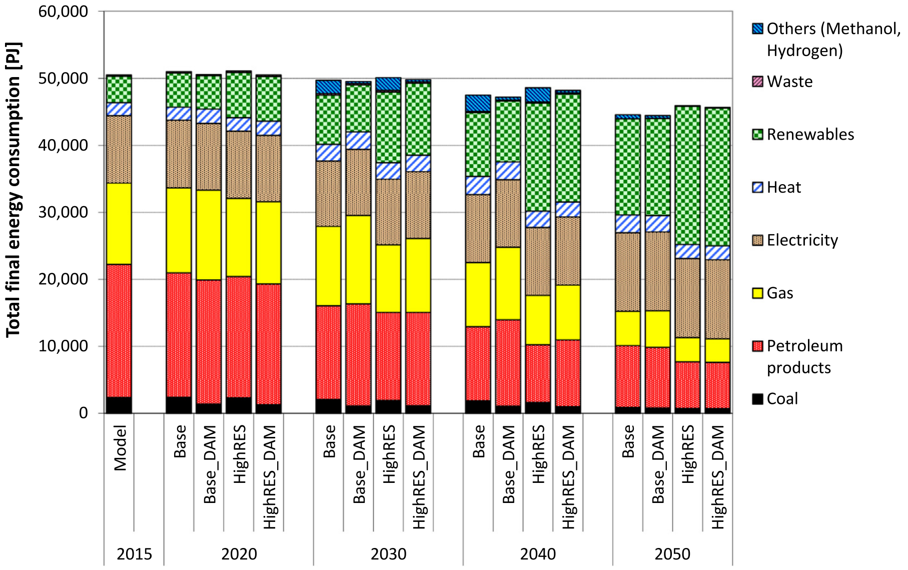

Fig. 2. Final energy consumption in EU-28 (PJ).

sources, the *Base* scenario overshoots the binding RES targets in 2020 and 2030 as set out in the *EU Renewable Energy Directives* [50,51]. Nevertheless, fossil fuel use is even more reduced in the *HighRES* pathway; these higher reductions are already visible in 2030 as the assumed 2050 targets are pushing forward renewable energy sources even more.

The main reasons for the increasing share of renewable energy sources in final energy consumption (renewable electricity excluded) can be found in road transport and the residential sector (Figs. 3 and 4). Since bio-based energy carriers are the only renewable energy sources with direct emissions of air pollutants, their utilization is visibly affected when associated health costs are taken into consideration (*Base_DAM* and *HighRES_DAM* scenarios), especially in the residential sector. Although all four scenarios are characterized by a steady increase in solar energy and ambient heat used in heat pumps as well as decreasing share of biomass over the years, the *Base_DAM* and *HighRES_DAM* scenarios show overall lower consumption of renewable energy sources compared to their counterparts (*Base* and *HighRES*, respectively). Internalizing costs of air pollution hampers biomass utilization in this sector (Fig. 3) since the respective heating technologies (stoves, wood/pellet boilers) are typically characterized by comparatively low efficiencies and high emissions of air pollutants. Instead, the model starts to invest in more efficient and clean natural gas technologies. This is especially the case in the transition years up until cost-efficient solar technologies and heat pumps are available on a big scale. In the case of the *Base_DAM* scenario, for example, the difference in biomass utilization is almost completely compensated by solar energy in 2050 when compared to the *Base* scenario. A similar compensation can also be observed in the *HighRES_DAM* run compared to the *HighRES* scenario. In these two scenarios, biomass utilization in 2050 is still higher compared to the other two scenarios in order to achieve the set RES targets. That this is even the case when costs of air pollution are considered as well (*HighRES_DAM*) underlines the crucial role of bio-based energy carries with regard to RES targets on final energy consumption.

In contrast, the share of biodiesel in road transport, as one of the few renewable possibilities in this sector, does not vary much between scenarios with and without internalized health costs. Especially in freight transport, existing low-carbon alternatives seem to be not competitive enough to serve the growing demand. In the case of RES targets as implemented in the *HighRES* scenario, biodiesel even becomes the main fuel in road transport from 2040 on in order to achieve the ambitious RES and GHG targets (Fig. 4). This effect can also be observed in the *HighRES_DAM* run although biodiesel is characterized by the same emission coefficients for air pollutants as conventional diesel vehicles. When air pollution is considered (*Base_DAM* and *HighRES_DAM*), fuel consumption in 2030 and 2040 is also notably higher compared to the other two scenarios (Fig. 4). To avoid emissions, the model invests in plugin hybrids, which are classified as electric vehicles and characterized by lower efficiencies once they switch to fossil fuel mode, increasing their fuel consumption in that case. Note that electric vehicles have a limited range and lower annual mileage making them unsuitable for long distances, which is why the model rather opts for new conventional or hybrid vehicles with high emission standards, especially for heavy-duty vehicles and buses. In the given scenarios, the impact of air pollution control on road transport is also limited by the model setup. All vehicles are equally characterized by emissions from abrasion processes (non-exhaust emissions) and with the new low emission standards of a modern car fleet, these processes are the dominant factor for primary particle emissions in road transport. These emissions and their associated costs can only be avoided if there is a shift in transport modes (e.g. from private to public transport). Such agent-based decisions are not part of *TIMES PanEU* and would require a different modeling approach such as including cross-elasticities for dynamic demand projections.

4.1.2. Power supply

The installed capacity development is one of the main indicators in the energy system to evaluate different decarbonization pathways in power supply. Fig. 5 shows the development of installed electric capacity in EU-28 over the years for all four scenarios.

Without external RES targets as in the case of the *Base* and *Base_DAM* scenario, the model invests in nuclear power as a low-carbon technology in countries which did not ban this type of energy. Compared to alternative low-carbon technologies, nuclear power has the competitive advantage of higher full load hours. Costs of air pollution in the *Base_DAM* scenario lead to a lower share of coal and lignite in installed capacity compared to the *Base* run, especially after 2030, when Carbon Capture and Storage (CCS) technologies become available. Their lower efficiency results in higher emissions of air pollutants compared to non-CCS power plants. This offsets CCS as a favorable GHG mitigation option. As a result, there is less ambitious CCS deployment and lignite power plants are decommissioned faster as lignite causes the highest amount of air pollution. To still achieve the GHG reduction targets, more wind power is utilized instead, which leads to a higher total installed capacity with natural gas as back up capacity, similar as in

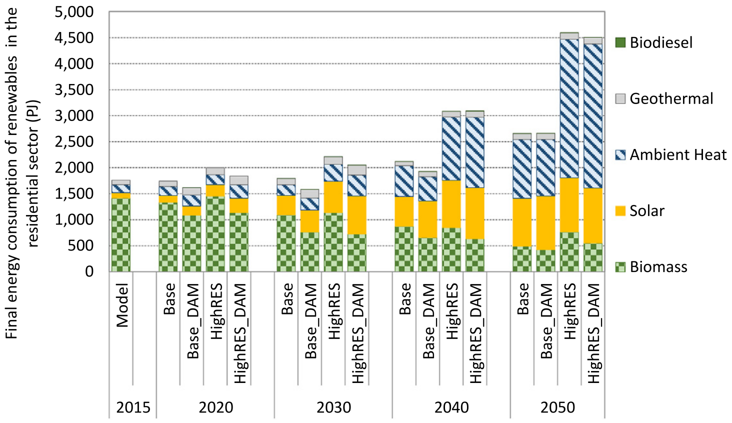

Fig. 3. Final energy consumption of renewables (excl. electricity) in the residential sector in EU-28 (PJ).

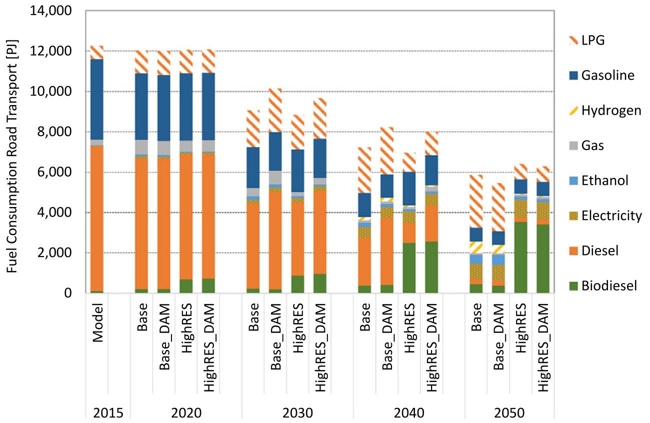

Fig. 4. Fuel consumption in road transport in EU-28 (PJ).

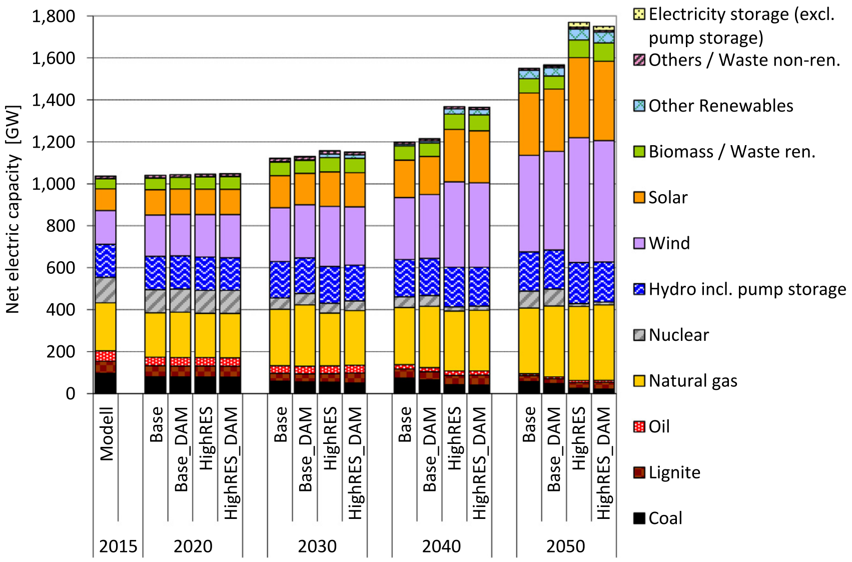

Fig. 5. Installed electric capacity in EU-28 (GW).

the *HighRES* pathway. In the *HighRES* scenario, the nuclear capacity is replaced by higher deployment of solar and wind energy to meet the set RES targets. Due to lower capacity factors of these technologies, the total installed capacity is also higher in this case, while the electricity production (Fig. 6) is almost at the same level compared to the *Base* run. The higher share of renewables also leads to higher deployment of natural gas as back up capacity, which is not utilized for electricity production as much as in the *Base* scenario. The fluctuating electricity supply by renewable energy sources also leads to a higher need for and utilization of electricity storages. Additionally, less biomass is utilized in both the *Base_DAM* and *HighRES_DAM* scenario. As a solid fuel, biomass has relative high emission coefficients, especially for particulate matter and NO_X, resulting in relatively high costs. Overall, the introduced costs on air pollution seem to have only a marginal impact on the electricity sector. One reason for this can be found in the already high regulations in the electricity and district heat production with respect to air pollution control. Strict limit values on emissions of air pollutants bring about relatively low emission factors compared to other sectors such as residential. The electricity sector is also one of the first sectors to be decarbonized. The ambitious GHG reduction targets already lead to a shift from fossil fuels which are also the main source of air pollutants. In other sectors, with less alternative low-carbon fuels, GHG reduction requires expensive technical solutions. Here, the incentive of air pollution control costs yields a higher effect in providing valuable benefits which may reduce GHG mitigation costs.

4.2. Social cost of the energy system

To assess the effect of changes in the energy system on air pollution and the respective gains or losses in social welfare, cumulative energy system costs and costs of air pollution are discounted to 2015. Compared to the *Base* scenario, all scenarios show rather similar results with respect to technical energy system costs (Table 4). Due to the dominance of technical energy system costs (more than a factor of ten higher than costs of air pollution), this is also valid for the total social cost. Please note that costs of air pollution – as calculated by *TIMES PanEU* in the current setup – do not reflect the actual damage costs of air pollution in 2015, and partly also in 2020, since none or only half of the damage costs are applied as additional cost factors in these years. To analyze the differences in total health impacts and associated costs in detail, it is necessary to re-run *EcoSense* for all scenarios, which was out of the scope of this study. Basing the analysis on the damage costs as calculated by TIMES PanEU is still sufficient to directly quantify the savings achieved by internalizing health impacts.

When comparing the *Base* and *HighRES* scenario, the higher share of renewables causes higher technical energy system costs. At the same time, costs of air pollution are reduced; yet, this is not sufficient to achieve an overall reduction in total cost compared to the *Base* run. In both scenarios, all emissions except SO_2 are 25% to 55% lower in 2050 compared to 2015 (Fig. 7). SO_2 emissions reach almost the same level

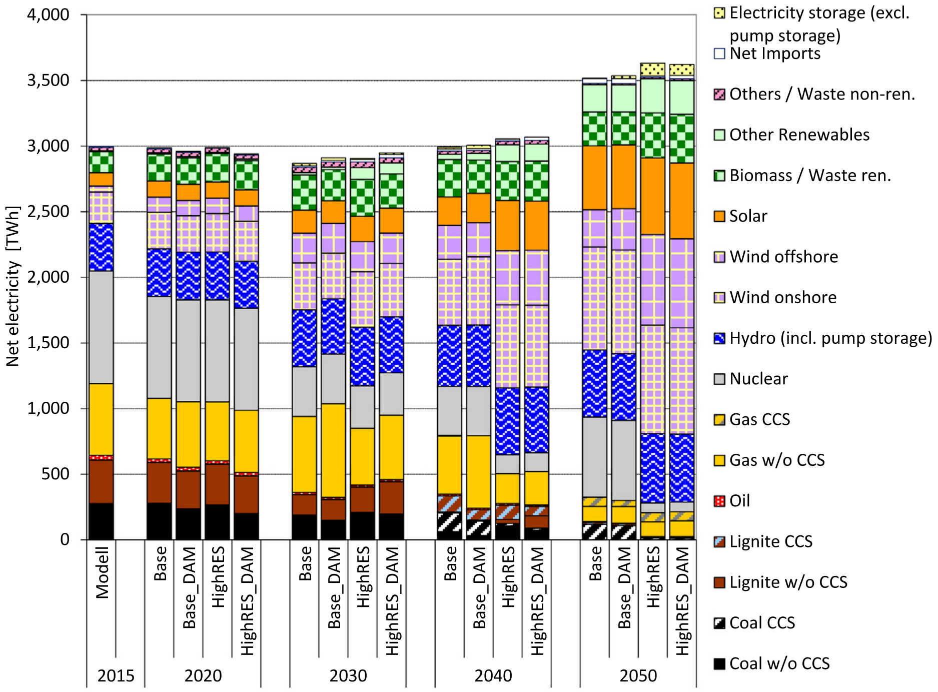

Fig. 6. Net electricity generation in EU-28 (TWh).

Table 4
Discounted costs (NPV 2015) expressed as differences to the *Base* scenario.

	Discounted[a] costs (bn €$_{2010}$)		
	System	Air pollution	Total/social
Base	64 730	2 912	67 642
ΔBase_DAM	164	−663	−499
ΔHighRES	629	−30	599
ΔHighRES_DAM	810	−628	182

[a] 5% discount rate assumed.

in 2050 as in 2015 in all four scenarios due to increasing demand and associated industrial process emissions as well as missing low-sulfur fuel alternatives, especially in navigation. The emission reductions are more prominent in the *HighRES* scenario, except for $PM_{2.5}$. Due to the high utilization of biomass, $PM_{2.5}$ emissions in 2050 are 3% higher compared to the *Base* scenario. Since this is the most critical pollutant with respect to health impacts, this small increase leads to almost the same costs of air pollution despite higher reductions of other pollutants. On the contrary, the high share of renewables in the *HighRES* scenario results in less carbon-intensive final energy consumption. Although all four scenarios implement the same decarbonization targets, carbon intensity in 2050 is about 20% lower when RES targets are in place (*HighRES*: $22\,\mathrm{kt}_{\mathrm{CO_2\text{-eq.}}}/\mathrm{PJ}$, *Base*: $28\,\mathrm{kt}_{\mathrm{CO_2\text{-eq.}}}/\mathrm{PJ}$[3]). Interestingly, the lower carbon-intensity is partly achieved by higher final energy consumption. Without RES targets, energy efficiency measures lowering final energy consumption are an important pillar of decarbonization, whose relevance diminishes with increasing utilization of carbon-free energy carriers.

Taking air pollution into account in the decision making leads to observable reductions in their associated costs. In both the *Base_DAM* and the *HighRES_DAM* scenario, technical energy system costs are almost the same as in their counterpart scenarios while costs of air pollution are reduced by around 20%. In 2050, emissions of all pollutants, especially emissions of the most critical pollutants concerning health impacts, are lower in these two scenarios compared to the *HighRES* and *Base* runs (Fig. 7). More importantly, emission reductions appear earlier in time. Without internalized costs of air pollution, the highest reduction appears after 2040, at the same time when the more ambitious GHG reduction targets come into force. In the case of air pollution considered in the optimization, the sharpest reductions occur already until 2030. The reason behind this is the principle of time preferences. As *TIMES PanEU* minimizes discounted total cost with perfect foresight, reducing expenditures in the first years is of greater value than reducing them in later years. This is why in the case of ambitious reduction targets in 2050, expensive GHG mitigation is pushed back resulting in a steeper decrease in emissions towards the end of the modeling horizon. In contrast, marginal damage costs are higher in the early years (see also Table 1). Therefore, the internalized costs have a bigger effect in the early years, leading to a sharp decrease from 2015 on, despite having only half of the actual marginal damage costs implemented in 2020. Overall, *Base_DAM* shows the highest cost reductions compared to the *Base* scenario in both costs of air pollution and total cost. The required share of renewable energy sources and their dependency on bio-based energy carriers seems to limit the reduction potential for air pollution in the *HighRES_DAM* scenario. Since the RES targets are defined as national aims, the chosen setup of country clusters does not necessarily lead to the actual social optimum in terms of resource efficiency across Europe. The utilization of fluctuating renewable energy sources like solar or wind energy strongly depends on underlying availability factors and additional constraints with respect to energy security. Still, internalizing costs of air pollution results in significant cost savings when compared to the *HighRES* scenario. Furthermore, *HighRES_DAM* and *Base_DAM* show lower carbon intensity than their respective counterparts. Even if these differences in carbon intensity are only minor, this supports the existence of mutual benefits as shown in previous studies [4,5]. However, it is not possible to quantify these mutual benefits with the current study design as this requires a reference scenario without ambitious GHG reduction targets, which is out of the scope of this study.

The share of sectors regarding the costs of air pollution is similar in all four scenarios with industry and transport causing the highest annual costs throughout all years. Both sectors are characterized by a

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[3] Applied GWP_{100} [52]: CH_4:34 N_{2O}: 298.

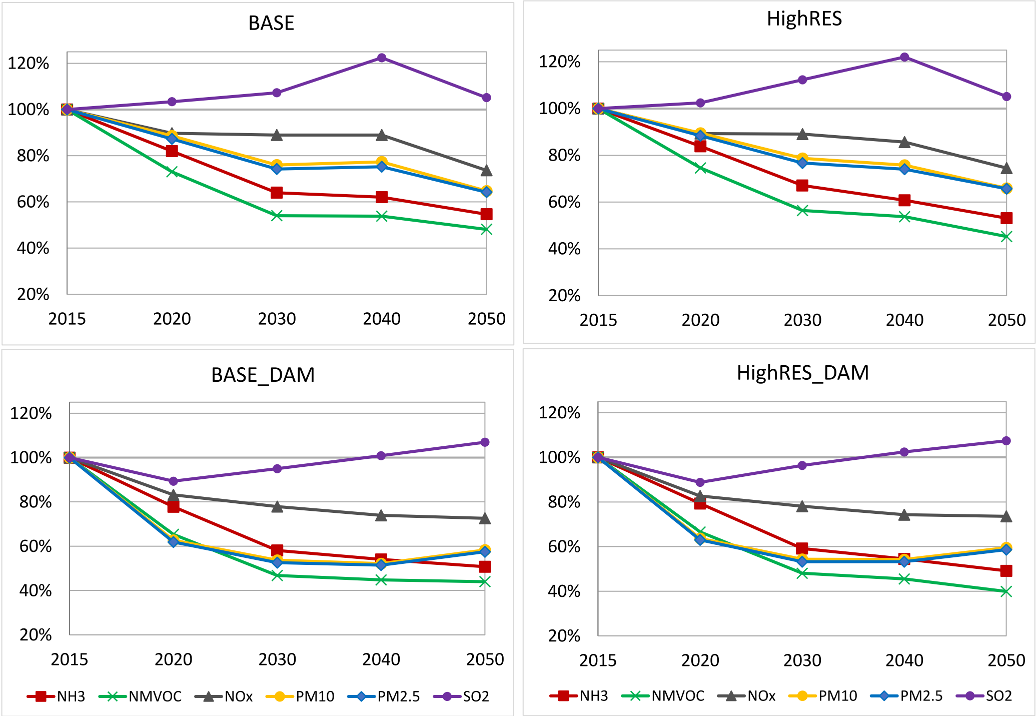

Fig. 7. Emission reductions of air pollutants rel. to 2015 levels in EU-28.

high share of non-exhaust emissions which cannot easily be mitigated by a shift in applied fuels but rather require additional end-of-pipe technologies or demand elasticities not included in the model to reduce air pollution. When comparing the two scenarios that consider air pollution in their optimization with their respective counterparts, differences in the annual costs of air pollution are still observable on sector level as depicted in Fig. 8.

In the early years, the differences mainly come from the industrial sector in which coal as one of the most relevant fuels in terms of air pollution is reduced. Additional gains come from reduced biomass utilization in the residential sector (see also Fig. 3). Some differences also occur in the transport sector, especially until 2040. When costs of air pollution are internalized, NO$_X$ and SO$_2$ emissions from navigation are reduced by partly replacing bunker fuel with diesel. In 2020 and 2030, this effect is bigger in the *Base* pathway, since a high share of biodiesel in road transport is needed in the *HighRES* pathway to achieve the assumed RES targets. After 2030, annual costs of air pollution from transport are further reduced due to the modernized vehicle fleet with lower emissions according to new emission standards. Visible reductions in the supply sector only appear in 2030 and 2040. In both the *Base* and the *HighRES* scenario, gasification and transformation processes are utilized in order to provide synthetic and alternative fuels. Such processes are known as important sources of NO$_X$, SO$_2$ and particulate matter. When air pollution is taken into account, these processes are not observed due to their high damage costs, resulting in significant cost reductions as depicted in Fig. 8. Since emissions in this sector are modeled in a simplified way based on fuel consumption only, possible end-of-pipe mitigation technologies such as flue gas desulfurization may, however, not be represented appropriately.

The differences between the individual sectors indicate that country- and pollutant-specific marginal damage costs may not be sufficient to capture the full benefits of air pollution control on GHG reductions. Marginal damage costs of specific emissions mainly vary with the affected population, which in turn depends on the location and height of the respective emission source. Taking into account typical release heights and locations of sources, sector-specific marginal damage costs could be calculated. However, such detailed cost-factors increase the complexity and thus needed CPU time, not only in the energy system model but also in the impact assessment model used to derive these cost factors. Therefore, it needs to be tested whether the additional insights outbalance this increase in complexity and how prospective insights vary with varying cost assumptions. Based on the current study, it can already be concluded that air pollution control and climate change mitigation policies affecting the energy system are most beneficial for the transition towards a low or zero carbon society when designed in an integrated manner.

5. Conclusions and further research

This study analyzed the effect of internalized costs of air pollutants on the European energy system for four possible decarbonization pathways until 2050. One scenario only considers ambitious GHG reduction targets (*Base*), the second one includes an additional constraint for a high share of renewable energy sources in final energy consumption (*HighRES*). To be able to study and assess interactions between air pollution control and GHG mitigation, emission factors for the main air pollutants as well as their respective marginal damage costs were introduced to the energy system model *TIMES PanEU* and optionally included in its optimization function (*Base_DAM* and *HighRES_DAM* scenarios).

With respect to energy system transformations, ambitious GHG reduction targets seem to be the most crucial driver, with all four scenarios showing similar total discounted cost, consisting of technical system costs and costs of air pollution. Additional RES targets in the *HighRES* scenario facilitate decarbonization but also lead to increased technical system costs which cannot be outbalanced by savings from reduced air pollution. When costs of air pollution are considered in the decision making, cumulative damage costs due to health impacts are still reduced by approximately 20% while the energy system costs vary only marginally. Although this is not sufficient to reduce total social cost substantially, this still means that the integrated approach on air pollution control and climate change mitigation results in welfare savings through avoided health impacts. Thereby, RES targets seem to be partially contradictory concerning air pollution control, as they

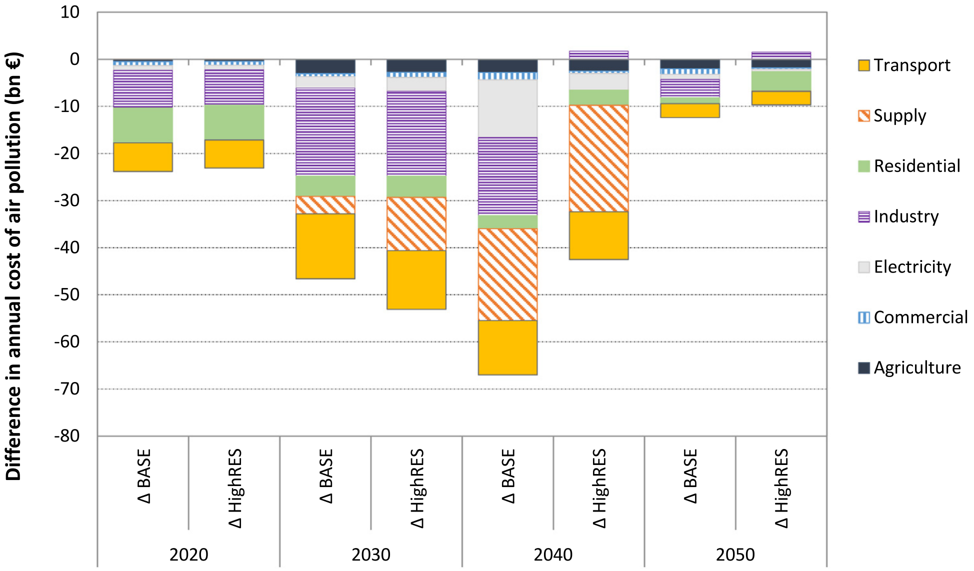

Fig. 8. Differences in annual costs of air pollution (bn $€_{2010}$) when considering health impacts (*Base-Base_DAM*; *HighRES-HighRES_DAM*).

lead to higher utilization of bio-based energy carriers in end-use sectors such as residential. While the *HighRES_DAM* scenario results in the highest decarbonization, the *Base_DAM* run shows the lowest social costs. Since the potential of renewable energy sources like solar or wind varies with geographic location, the assumed country clusters and resulting national targets may not reflect the optimal and most efficient utilization of renewable energy sources across Europe. Different country clusters may end up in a more favorable distribution across all countries, achieving the same high decarbonization and lower social cost simultaneously. This clearly shows how air pollution control and climate change mitigation policies interact with each other; they can either be beneficial for or hamper each other. Depending on which matter is seen to be the most pressing one, compromises may have to be made, particularly with air pollution being a rather local issue and climate change mitigation requiring common, global effort. In any case, air pollution control and climate change mitigation policies and their impacts should be considered simultaneously, resulting in an integrated framework.

It is also noteworthy that all scenarios lead to similar reductions in almost all emissions. Thereby, emissions are reduced earlier in the case of internalized costs of air pollution, indicating that an integrated perspective on climate change and air quality may motivate an early transition towards a low- or zero-carbon society. As the results indicate, SO_2 is the only pollutant that cannot be reduced in any of the scenarios. The simple approach to model emissions only based on the fuel type consumed in the supply sector may result in overestimating emissions of the applied gasification processes. Additionally, it may be necessary to introduce alternative low-sulfur fuels or technologies, e.g. in navigation, in order to be able to achieve actual reductions in SO_2. Similarly, changes in road transport are limited as agent-based decisions are not part of *TIMES PanEU*. Shifts from one transport mode to another can only be modeled exogenously as scenario-specific assumptions. Especially with regard to air pollution control, this is, however, a crucial mitigation option as all road vehicles produce non-exhaust emissions from abrasion processes. These can only be avoided by reduced vehicle-kilometers; either as a result of reduced transport demand or of a shift from private to public transport. Future research on sector-specific impacts should thus investigate the effect of possible alternative fuels and demand elasticities to also reduce process-related emissions.

With the current setup and applied scenarios, it is not possible to quantify mutual benefits of air pollution control and climate change mitigation in terms of attributable decarbonization or mitigation costs. Nevertheless, the lower carbon intensity of final energy consumption in both scenarios with internalized costs of air pollution indicates that such mutual benefits exist. For future research, the applied framework should thus include a scenario without ambitious GHG targets to see the potential of air pollution control costs to reduce GHG emissions and to quantify benefits as changes in mitigation costs of both climate change and air pollution. Especially in the case of national targets, their distributional effects should be investigated further. By studying health impacts and their associated costs on the country level, winners and losers in terms of air quality can be identified. This should include a sensitivity analysis with regard to marginal damage costs and their impact as their uncertainty should not be underestimated. To further generalize the given implications, the same scenarios should also be analyzed based on different models or model configurations. Furthermore, additional scenarios should consider varying combinations of targets (national vs. Europe-wide) as well as different instruments to reduce GHG emissions (e.g. CO_2 prices) to better study the interplay between national, European-wide and global ambitious with regard to air pollution control, climate change mitigation and renewable energy sources.

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3.3 Publication III

A comparison of three transformation pathways towards a sustainable European society - an integrated analysis from an energy system perspective

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A comparison of three transformation pathways towards a sustainable European society - An integrated analysis from an energy system perspective

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ABSTRACT

An energy system transition in the European Union is required to meet the decarbonisation targets determined in the Paris Agreement. To realise this transition, a reduction in greenhouse gas emissions of at least 80% from 1990 levels by 2050 is required. However, ambitions are being raised towards carbon neutrality. Such transition will likely imply deep changes across all sectors of the EU economies and societies. The impacts on these sectors need to be analysed with a multi-disciplinary approach, to unveil cross-sectoral risks and opportunities of the transition. Additionally, the pace and effectiveness of the transition may be affected by technical and economic drivers within the EU. In this paper, we soft-link three modelling frameworks specialised in assessing technology transitions, spatially-disaggregated health impacts of air pollutants and economic impacts and we apply them to the study of deep decarbonisation pathways for the EU. An energy system model, TIMES PanEU, is soft linked with an impact assessment model, EcoSense, and with a general equilibrium model, NEWAGE. The application looks at three clearly distinguished but likely paths: one where the decarbonisation effort is mostly undertaken by decarbonisation of the energy supply; one where consumers take on a more active role in the decarbonisation, instead; one where ambitions are raised and all sectors of the economy must act together to achieve the targets. In the specific application, it is concluded that 80% reduction is achievable with a decentralised, demand driven system as well as with a centralised one, where the decarbonisation effort mainly comes from the supply side. On the other hand, to achieve a more ambitious reduction target, a broader technology mix and also the effort from both supply and demand side will be required. The synergy between the sectors, especially for the utilisation of the domestic sources such as biomass, will be a decisive factor for the direction of the energy transition.

1. Introduction

1.1. Motivation

The Clean energy for all Europeans strategy [1], issued in 2016, and the Clean Planet for all strategy [2], issued in 2018, support the implementation of the Energy Union and set high decarbonisation ambitions. The required effort to achieve this transition is a minimum of 80% greenhouse gases (GHG) emission reduction by 2050 compared to 1990, but net zero emission targets are also discussed [2]. Such targets can be achieved following different paths. However, each path implies radical transformation of the energy, agriculture, industry, residential and transportation sectors, it imposes changes from transnational, to national and local scale and it affects several dimensions of European societies. As hinted at in the Clean Planet for all strategy [2], challenges emerge in several areas comprising geopolitical developments and global economy, cross-sectoral impacts and resource availability, technology innovation as well as impacts of and on the society including health.

An effective decarbonisation process must consider these complexities jointly and multi-model quantitative assessments can bring a contribution in this direction.

1.2. Background

The European Commission’s strategies have been supported by

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model-based analyses carried out with a suite of tools including PRIMES, PROMETHEUS, GAINS, GLOBIOM and GEM-E3. In the Energy Roadmap 2050 [3], for a number of decarbonisation scenarios, this suite of models computes quantities related to the evolution of the energy sector and its impacts on climate and air quality (in terms of CO_2 and non-CO_2 emissions), economy (impacts on GDP and job market), society (especially households expenditure) and resource use (land and water). They followed an impact oriented approach in their study but not an integrated approach.

80% GHG reduction in the EU27 as a whole is studied in Ref. [4]. The PRIMES model is applied in the study and the focus is on the impacts of technology developments on several transition pathways. The study discusses the role of mitigation technologies such as CCS and electric vehicles on the achievement of the target and it finds that both options are key for the target to be achieved. The findings of PRIMES are confirmed in a study carried out within CECILIA (Choosing Efficient Combinations of Policy Instruments for Low-carbon development and Innovation to Achieve Europe's 2050 climate targets), a EU funded action as well [5]. The action provides model-based insights on the potential success and impacts of decarbonisation policies. It measures their effects on equity, competitiveness and innovation. The assessment complements and validates the one run for the Commission's Energy Roadmap 2050 [3], with a different set of modelling tools (a European energy model based on TIMES, an environment-economy model named GINFORS and an Input-Output model named EXIOBASE). The main insights on the energy system transformation from the scenario analyses unveil challenges of the targets proposed by the Energy Roadmap 2050: 80% cut in emissions seems not to be feasible without negative emissions from biomass CCS; industry is the highest sector to decarbonise. However, the modelling work in the action presents challenges, as to what assumptions are made about future developments (e.g. GDP, energy prices, population) across all modelling tools.

80% reduction is again studied in Ref. [6], using the European TIMES model ETM-UCL. The focus of the study lies mainly on the power sector and availability of a specific mitigation technology, biomass-based CCS (BECCS). The use of such a carbon-negative technology to reduce emissions gives more flexibility to other sectors in the energy system. The availability of BECCS in the energy system decreases the CO_2 mitigation costs as well, according to the findings.

Beyond 80% reduction is analysed in Ref. [7]. The JRC-EU-TIMES model is applied to study an 85% reduction target. However, the focus of the study is limited to the power sector and it draws conclusions only on the role of power supply technologies in the future energy mix. The impacts of the timeline of CCS, renewable potentials, limited nuclear deployment, low energy consumption in the energy system, low biomass availability and low solar and wind share in the electricity generation are assessed in several scenarios. Based on their results, the importance of nuclear acceptance and availability of sites for new renewable energy plants are highlighted. Nuclear and solar PV are identified as key technologies. Conventional CCS technologies, hydro, wind onshore, wind offshore, bioenergy, marine and geothermal follow in terms of relevance. The study also concludes that R&D priority should be given to technologies that can be deployed quickly to reduce the total system cost in the transition. However, as the study mainly focuses on the power sector, the transition in the other sectors is not analysed.

A Clean Planet for all strategy [2] has different scenario analyses, assessing the role of different energy carriers to fulfil 80% decarbonisation targets. In one scenario, electrification plays the main role; whereas in the others priority is given to hydrogen-based technologies in transport, industry and buildings. E-fuel options in industry, transport and buildings, deep energy efficiency and increased resource and material efficiency are determined as main drivers. 90% and 100% reduction targets are also investigated, considering availability of all the above mitigation options, including BECCS and other carbon storage technologies. However, in this case the interactions between the GHG reduction targets in the energy system and the economic system and society are only studied to a limited extent without considering the feedbacks from one to another.

Except for [2], above mentioned studies analysed the transition up to 85% reduction and each of them focused on a specific sector and mainly on the role of specific technologies. On the other hand, in Ref. [2] reduction ambitions are raised and beyond 85% reduction scenarios are investigated. However, their study is also mainly focused on the technological developments and impacts of these developments in the energy transition. Additionally, possible feedbacks from the macro-economic variables as well as from air pollution control are not considered in their energy system analyses. The cause-effect relationships between interconnected sectors during the transition have not been addressed in any of these studies as well.

1.3. *Research aim & structure*

The need for further studies on the impacts of decarbonisation is clear. This paper aims to further our understanding by testing the cause-effect relationship between interconnected sectors. This is done by developing system-focused analyses of historical trends and technological developments, where feedback from air pollution (further referred to as externalities) and macro-economic variations in the energy system are considered. An integrated modelling framework considering the above factors is employed. This framework is applied to three representative transformation pathways for the EU energy system. In the first two pathways, an 80% GHG reduction target with distinct driving forces is assumed. In the third pathway, an ambitious 95% reduction is explored. The results of these pathways are compared to determine the robustness of the findings and to provide policy insights toward the energy transition.

The study is structured as follows: In Section 2, the methodology is explained with sub-sections about the applied model TIMES PanEU and its further development with the integration of externalities and macro-economic variations (Section 2.2. & 2.3.). The pathway narratives and their translation into modelling assumptions are described in Section 3. Section 4 analyses the insights from the model-based assessment and discusses the findings in the study by comparing some of the insights with the latest scenario analyses in Ref. [2]. Finally, main conclusions and further research areas are identified in Section 5.

2. Methodology

2.1. *TIMES PanEU model*

TIMES PanEU is employed as an energy system optimisation model to analyse the energy system transition towards a low-carbon EU energy system in our study. We chose TIMES PanEU since it fits our requirements to draw policy relevant insights based on system interactions and has already been applied and reviewed in different studies focusing on the energy system transition [8,9].

TIMES PanEU is built with the TIMES model generator, in the modelling environment GAMS. It is a model generator to create bottom-up energy system models with linear programming. It has been developed and maintained within the Energy Technology System Analyses Program (ETSAP) by the International Energy Agency (IEA) [10]. The data management system (VEDA-TIMES) creates an energy system model [11]. Through this data system, the input data, the structure of the model and all the scenario-related information are given to the model and they are converted to mathematical equations. Under standard settings, the model aims to minimise the total discounted system cost in a given timeframe to meet exogenously given energy service demands [12] with a perfect foresight principle. The TIMES model generator has already been applied in similar energy system transition studies [4,7] and thus proved itself to be suitable for such an analysis, especially when providing insights to policy makers.

TIMES PanEU covers the European Union countries as well as

Norway and Switzerland and each country represents a single region in the model. The modelling horizon spans from 2010 to 2050, split into 5 year-time steps. A year is divided into 12 time-slices, 4-seasonal and 3-day level (day, peak and night). Greenhouse gas emissions (CO_2, CH_4, N_2O) are included in the model. The basic structure of the model is called reference energy system (RES). RES includes all relevant energy, material, and emission flows from the primary production to meet the energy service demands for each region defined in the model [13]. RES of the model covers the entire energy system, from the supply of resources to energy service demand. Fig. 1 shows the interactions between the different parts of the system and outputs calculated after each step in a reference energy system. With its sectoral structure and spatial resolution, TIMES PanEU provides the possibility to address the sector integrations as well as interactions between the different Member States. This is important, for instance, with regard to potentials of the domestic sources such as biomass: these sources need to be evaluated not only at the sectoral and country level but also considering the interactions between sectors and the possibility of trade between Member States. To enable such integrations and interactions between different parts of the European energy system, several technological options are modelled. To model a technology, parameters such as investment cost, efficiency, variable operation and maintenance cost as well as fixed operation and maintenance cost, fuel cost, emission factors and availability factors are required.

Primary energy sources are modelled according to country potentials and the trade possibilities from the neighbouring countries. Different cost potential curves are defined for each of the sources such as crude oil, natural gas, coal, lignite etc. The World Energy Outlook 2016 prices [14] and average country mining costs are taken as reference to determine the cost figures. Various bioenergy carriers are included by taking into account the country potential and their costs. No constraints are considered for biomass trade. Land availability for biomass cultivation is given in the model based on [15]. Moreover, other conversion technologies such as refineries, gasification and Power-to-Gas are part of the model [10].

In the electricity sector, the electricity supply at different voltage levels is modelled through different technologies. In the system, the large central power plants feed to high voltage grid, while decentralised generation such as from PV systems feeds to medium and low voltage grids. The technologies which exist at the start of the modelling period and those considered as future options are classified according to the input fuels and technology type. They are aggregated by power plant type. New technologies such as electricity storages, hydrogen technologies and CCS technologies are modelled as investment options during the time horizon. The availability of certain technologies such as CCS is determined according to the expected availability of the technologies in the market [16]. Cogeneration plants (CHP) for centrally supplied district heat are given as a choice in the model to provide both electricity and heat. Power-to-Heat technologies together with heat storages are applied in the public heat supply [16].

The industrial sector is divided into energy-intensive and non-energy-intensive industries. The energy intensive industries cover the categories iron and steel, aluminium, copper, ammonia, chlorine, cement, lime, flat glass, and paper; whereas the non-energy intensive industries include other non-ferrous metals, other chemicals, other non-metallic minerals, food and tobacco and other industries. Industrial auto producers are also modelled [17]. There are two approaches to model the energy inputs within the industrial sector of TIMES PanEU: the process-oriented and application-oriented modelling. The process-oriented approach is applied to model the energy-intensive industries, while the application-oriented is used for the non-intensive industries. In process-oriented modelling, the demand of certain production goods must be met in terms of physical quantities (Mt). This demand is given exogenously to the model. Different technologies with different technical and economic parameters are available at different production stages to meet the demand. The choice of technology is a result of the optimisation. The modelling of non-energy-intensive industries is based on energy application types and requires different types of useful energy. The demand thus refers to an amount of energy (i.e. in PJ) instead of physical quantities. The useful energy demand of the non-energy- intensive industries is divided into different groups according to different types of application of industrial energy use. These include thermal applications (space heating, hot water, process heat, steam), electric motor applications (pumps, compressed air, fans, refrigeration, other motor applications) and other applications such as lighting, electrochemical conversion processes and other applications.

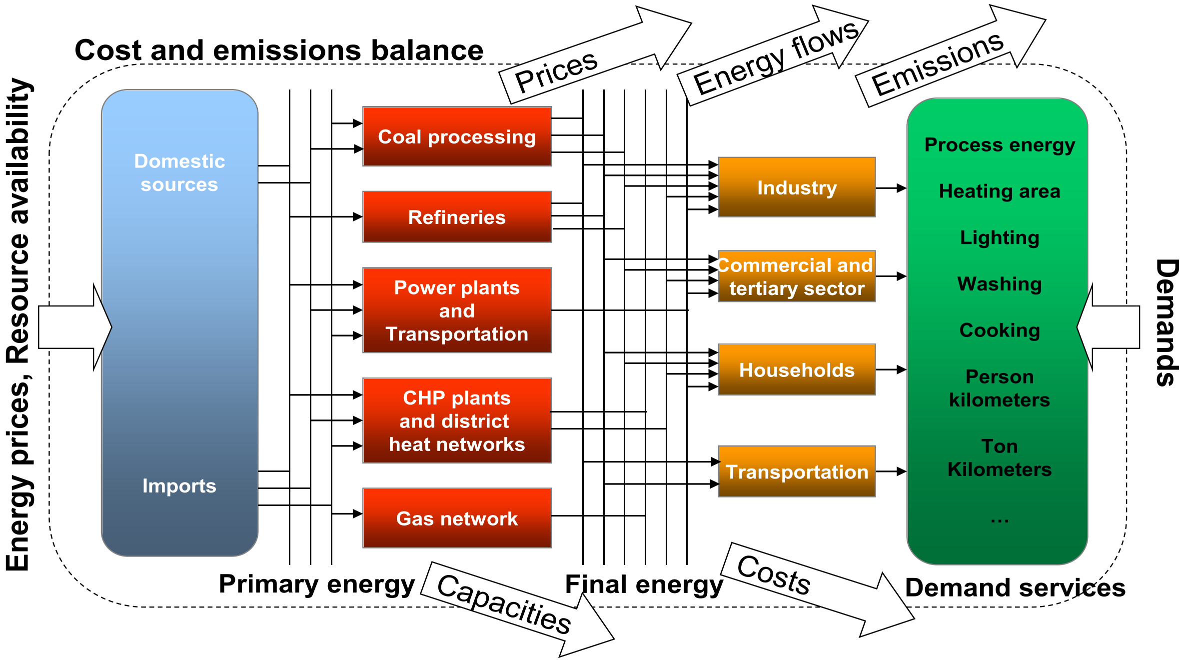

Fig. 1. TIMES PanEU reference energy system [10].

The starting point for this modelling is again the results of the analysis of the industrial sector. To satisfy the demand for useful energy, the model has different processes with different efficiencies and costs at disposal. For example, boiler plants or industrial CHP, each based on different fuels, are available for heat supply [17].

In the household, commercial and agriculture segment, the energy service demands are disaggregated according to different sectors. Various technologies, aggregated according to technology type and energy carrier, are implemented to provide the energy service demands. There is a further disaggregation of household energy service demands to space heating single family urban and rural, space heating multi family, water heating, space cooling, lighting, cooking, refrigeration, cloth washing, drying, dish washing, other electric and other energy. The process to supply the agriculture demand is defined as one general process. Commercial energy service demands are also further disaggregated to space heating large and small, space cooling large and small, lighting, cooking, refrigeration, public lighting, other electric and other energy. The underlying assumptions of the existing energy service demand figures according to disaggregation in TIMES PanEU are consistent with the socio-demographic assumptions of the EU Reference Scenario [18]. To cover the scope of the Paris Agreement, non-energy GHG emissions from the agricultural sector are modelled as well along with the certain mitigation technologies. These emissions are caused by the use of fertilizers and by livestock (manure management, enteric fermentation).

The transport sector is disaggregated according to transportation mode: car, bus, motorcycle, passenger train, freight, air traffic (external and internal) and navigation categories. The passenger transport is modelled in the unit of Passenger-km (Pkm). The freight is modelled in Ton-km (Tkm). Different vehicle technologies based on the different energy carriers are modelled for each demand category mentioned above. Hybrid technologies are also available in the technology mix.

Mitigation options are also modelled to decarbonise the aviation and navigation sectors. These transportation modes are modelled as generic processes in TIMES PanEU which means there is not any defined investment cost and the cost optimisation of the system only depends on the cost of the fuel and the CO_2 emission coefficient. In Ref. [19], the milestones in terms of technology improvement are defined to decarbonise these sectors. These milestones are considered in TIMES PanEU as annual constraints to the availability of the technologies. In aviation, bio kerosene for domestic and international flights is defined as an option starting from 2015. Biodiesel for domestic flights starting from 2025 and international flights from 2035 on is given an option. Maximum 10% of the demand of the domestic flights can be met through electricity and 10% again through hydrogen. These levels increase to 15% electricity and 20% hydrogen by 2050. These values set as maximum 5% for the share of electricity and hydrogen in the energy carrier mixture for international flights. The share of hydrogen is increased to 10% in 2050. In navigation, LNG, biodiesel and bio kerosene are defined as options starting 2025, in line with the milestones in Ref. [19]. LNG prices are based on the World Energy Outlook [14]. Electricity and hydrogen are given as options starting from 2035 and the shares kept at maximum 10% for the international bunker and for the domestic. Electricity is increased to 50% in 2050.

To also consider the impacts of economic variations and externalities on the energy system transformation, the model has been extended for this study as described in Section 2.2 & 2.3.

2.2. Integration of externalities

The EU has targets to reduce energy related CO_2 emissions but there is no single EU target to reduce emissions of air pollutants [20]. Instead, national emission caps are determined for each Member State and the responsibility belongs to national governments to achieve these. GHG and air pollutants result from the combustion of fossil fuels in the energy system. Therefore, the synergies between GHG reduction targets and air pollution mitigation policies should be addressed in the transition towards to a low carbon EU society. Such synergies may reduce health impacts of emissions, especially in cities and densely populated areas. Additionally, they may bring savings on health costs. These costs reflect the monetary loss in welfare. This part of work aims at illuminating cause-effect relationships between energy related emissions and health costs for the citizens. As noted above, this is not considered in the latest scenario analyses carried out in Ref. [2].

2.2.1. Linking TIMES PanEU with ecosense

To consider the externalities and their impacts in the energy system in this study, TIMES PanEU is linked to the health impact assessment model EcoSense [21]. For the integration of the external costs, as a first step, the emission coefficients of the pollutants SO_2, NO_x, NH_3, volatile organic compounds (VOC), $PM_{2.5}$ and PM_{10} (in kt/PJ) are updated in TIMES PanEU. The coefficients are disaggregated according to sectors, regions and technology types in the energy system. The external costs, provided by EcoSense as unit damage cost factors, are integrated to the model through the data exchange between TIMES PanEU and EcoSense [9]. Fig. 2 shows the data exchange. All cost factors are calculated as EUR 2010/kg by EcoSense and implemented as linear cost functions in TIMES PanEU according to the methodology described in Ref. [22]. These cost factors [21] are introduced into the model starting from 2020 and these costs are not taken into account in the system design in reality. As the cost factors will be added into the energy system model's optimisation function to approximate a policy decision to have a tax on externalities, it is assumed they would be 'phased in' gradually with only half costs for in 2020. This stepwise introduction also matches with the 5-year model structure of TIMES PanEU [9]. From 2030 on, the calculated unit damage cost (€/kg) values by EcoSense are employed directly in the model.

The health damage costs can be used for two types of assessments in energy system modelling:

- To provide an exogenous economic evaluation of the health damages by the energy system, without any feedback to the cost optimisation function (ex-post);
- To study how the optimal energy supply mix would change, if health damage costs were to be internalised, as part of the cost optimisation function (ex-ante). This would correspond to a scenario were a taxation is introduced on emissions, equivalent to the health damage the emissions are likely to cause.

2.2.2. Impact of externalities in the energy system

A pre-assessment is carried out to show the impact of internalising externalities. We have compared the case where health damage costs from emissions in the energy system are considered as part of the cost optimisation in TIMES PanEU (ex-ante) and where they are not (ex-post). The comparison is developed for 80% GHG reduction scenario which aims 80% reduction of GHG emissions compared to 1990 level as discussed in Refs. [1,2]. Socio-economic assumptions of this scenario are based on EU Reference Scenario [18]. This scenario does not have any detailed assumptions related with the reduction targets which are defined in Section 3. In this section, the results for the selected indicators; final energy consumption in the residential and agriculture sectors, are shown. These indicators are selected since both sectors are characterized by lower emission standards of air pollutants and typically by less efficient technologies (small scale applications). In contrast, sectors such as electricity generation, industry or transport have already strong regulations with regard to the application of technical measures to reduce air pollution. Thus, the impact of additional costs on air pollution is most visible in less regulated sectors such as residential and agriculture. In all the pathways from which the results are given in Section 4, the damage costs are considered in the optimisation function (ex-ante).

In Fig. 3, when the damage costs are considered in the optimisation

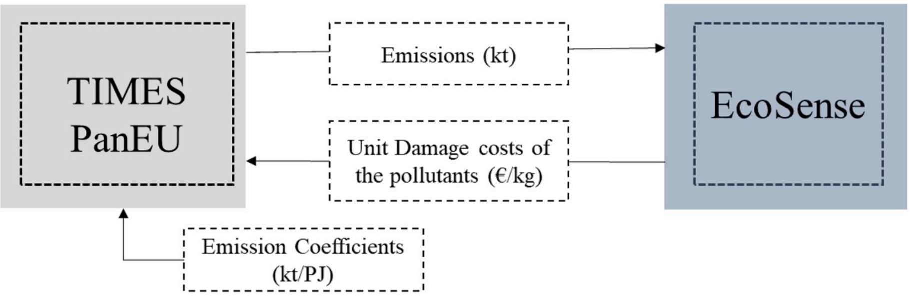

Fig. 2. The link between TIMES PanEU & EcoSense.

function (GHG_DAM), the share of biomass decreases over time compared to ex post run (GHG) and it halves in 2050 in GHG_DAM. The decrease is mainly compensated with gas and ambient heat in the residential sector as well as with the savings process. The role of savings can be seen from the difference of total final energy consumption between the two scenarios. This is due to biomass combustion processes causing higher levels of air pollution compared to modern heating systems powered by gas or electricity, which results in particularly harmful health impacts on the local level.

Internalising the damage costs impacts the least-cost energy mix in the agricultural sector starting from 2020, as can be seen in Fig. 4. With the inclusion of the damage costs, coal does not have a share in the final consumption and the share of renewables experiences a decrease, mostly due to decreased use of biomass. The latter is mainly due to the higher emissions of particulate matter by biomass combustion, which have high health impacts. The reduction of coal and biomass uses are compensated with the higher share of gas.

2.3. *Integration of economic variations*

An energy transition implying deep fuel shifts and significant investments towards decarbonisation is likely to carry impacts on economies, for example in terms of GDP growth, job market or gains and losses in competitiveness. Winners and losers may arise among the EU Member States. Studying these dynamics is the key to understand opportunities and threats of the decarbonisation of the energy system. However, as much as the development of the energy sector has implications for the whole economy, conversely the whole economy (especially changes in fuel prices, population and GDP growth) has impacts on the demand-supply equilibrium in the energy sector.

2.3.1. *Linking TIMES PanEU with NEWAGE*

To capture the cross-impacts from the macro-economic variations through the energy transition, a bi-directional, iterative link is established in this study between NEWAGE, a general equilibrium model [23], and the energy system model TIMES PanEU. The models are iterated by updating the energy service demands in TIMES PanEU based on the GDP and sectoral developments calculated in NEWAGE. In NEWAGE, electricity generation values are updated with the electricity generation results from TIMES PanEU. The GDP and sectoral development results from NEWAGE are not fully reflected in the energy service demand figures in TIMES PanEU. Instead, a decoupling factor is chosen to appropriately reflect the effect of social and technical developments on energy service demands, such as population growth, changes in behaviour and efficiency improvements, which effectively decouple energy demand from economic growth [24]. The underlying socio-technical factors on demand developments in TIMES PanEU are assumed to be consistent with the EU Reference Scenario [18]. Based on experiences in the similar studies [25–27], a decoupling factor of 0.33 is thus applied with regard to the integration of NEWAGE developments in TIMES PanEU. This means that only 33% of the development in energy service demands is assumed to be directly influenced by the general economic development of a region. The iteration process is carried out in all the pathways until the models converge in electricity generation and energy service demands.

The modelling steps for this coupling are:

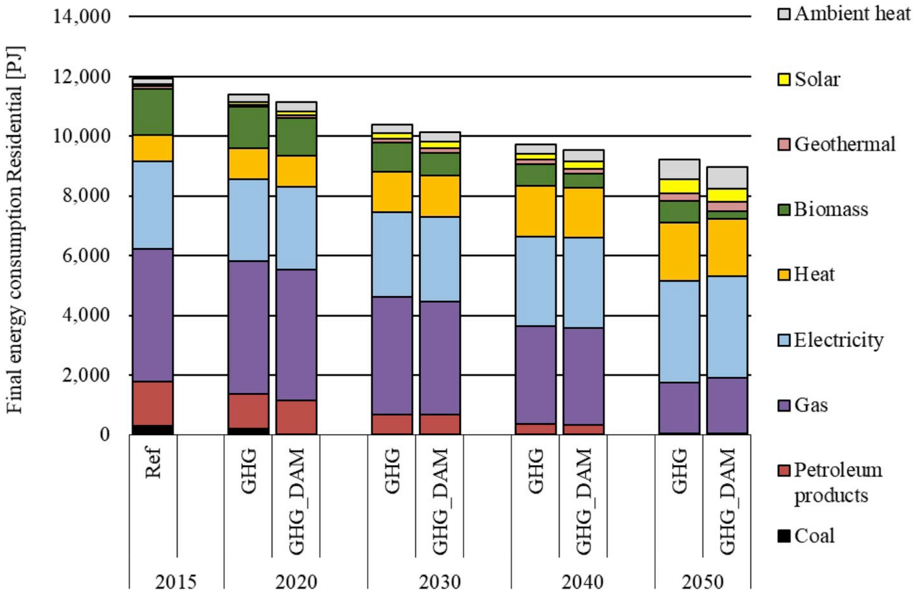

Fig. 3. Final energy consumption Residential in the EU28 in the illustrative scenario - Effect of externalities.

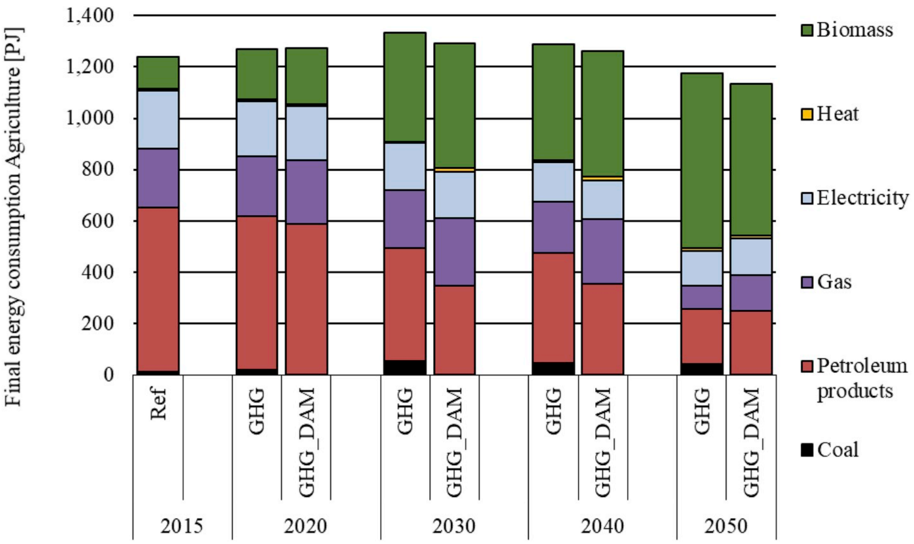

Fig. 4. Final energy consumption agriculture in the EU28in the illustrative scenario - Effect of externalities.

1. Energy service demand projections are updated in TIMES PanEU based on results of NEWAGE.
2. TIMES PanEU provides the results of a decarbonisation scenario, where there is a target to reduce GHG emissions, to NEWAGE as shown in Fig. 5.
3. NEWAGE calculates the updated energy service demand growth patterns based on the results of TIMES PanEU after the data exchange.
4. This process is repeated until the results of the two models reach equilibrium, until their electricity generation mix according to energy carriers converges.

The data exchange can be seen in Fig. 5. In all the results from the pathways discussed in Section 4, the two models are soft linked and reached the convergence. Selected insights from this linkage are given in the following section for an illustrative scenario structure.

2.3.2. *Impact of macro-economic variations in the energy system*

In this section, an example from results is shown from the coupling of energy system model with the macro-economic model NEWAGE. The iteration process is required to reach convergence between the models and this process is first attempted with an illustrative scenario including an 80% reduction target based on the 1990 level as discussed in Refs. [1, 2], similarly in Section 2.2.1 and without considering health damage costs in the optimisation. Socio-economic assumptions of this scenario are based on EU Reference Scenario [18].

According to the process described in Section 2.3.1, with the above defined 80% reduction scenario, the models reach convergence after the 5th iteration. By considering the GDP and industrial growth development paths calculated by NEWAGE in TIMES PanEU demand figures, the commercial demand decreases. This is visible in the final energy consumption of the commercial sector illustrated in Fig. 6. In this representative case, only 33% of the demand development path is based on the NEWAGE results. 66% of the trend still comes from the original demand assumptions as explained in Section 2.3.1. Therefore, the effect of the link is dampened in the results. However, the effect is expected to increase where the demand development is based on the results of the macro-economic model with higher decoupling factor.

As a result of the link created between the models, a slight decrease is observed in the commercial development in NEWAGE, which results in a 3% reduction in the final energy consumption in the commercial sector. NEWAGE, as a general equilibrium model, has the flexibility to change the demand to fulfil the given GHG reduction target. Compared to the EU Reference Scenario [18], the energy service demands for the commercial sector such as commercial cooling, cooking, heating, lighting are decreased in NEWAGE in the illustrative 80% reduction scenario. This change in the demand also results in lower sectoral growth rate in this sector. Therefore, above mentioned energy service demand figures in TIMES PanEU for the commercial sector experience small reductions compared to figures assumed according to the development in the Reference Scenario [18].

3. Scenario development

The aim of the REEEM Project [28], which this study is based on, is to gain a clear and comprehensive understanding of the system-wide

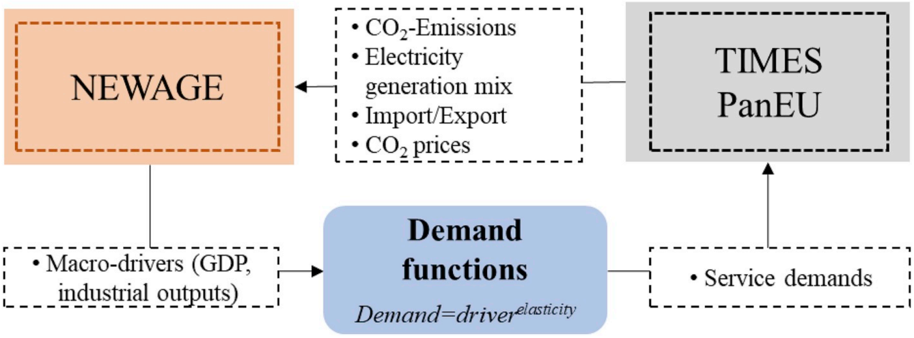

Fig. 5. The link between TIMES PanEU & NEWAGE.

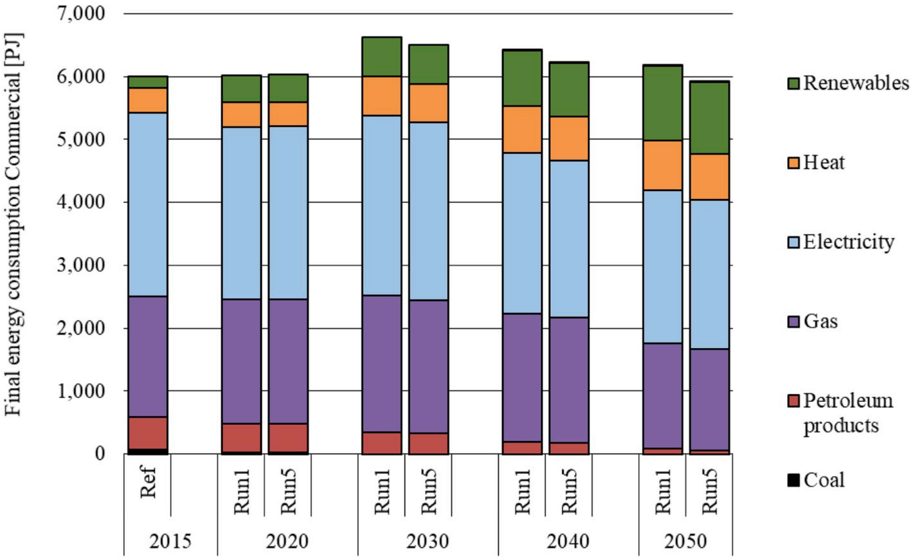

Fig. 6. Final energy consumption commercial in the EU28 in the illustrative scenario.

implications of energy strategies in support of transitions to a competitive low-carbon EU energy society, given the objectives and framework outlined in the Strategic Energy Technology Plan. To fulfil this aim, three pathways are designed to investigate the potential dynamics of the different decarbonisation paths in the energy transition, looking at different trends which are likely to occur in the EU [29]:

- Coalitions for a Low-carbon future (CL): energy carrier suppliers take on the highest burden in the decarbonisation of the EU energy system, while consumers observe it mostly passively or respond to policies as they come.
- Local Solutions (LS): consumers (especially households) engage in the transition towards a low-carbon energy system, by choices on end use appliances, energy efficiency measures and transportation technologies.
- Paris Agreement (PA): the EU undertakes an ambitious decarbonisation effort, with a target of 95% reduction of CO_2 emissions by 2050. This overshoots the Paris Agreement pledges and is more in line with the discussed carbon neutrality. Both energy carrier suppliers and consumers engage in the challenge.

These three pathways were defined in the project in two main steps:

1. Definition of the overarching narrative (storyline) during stakeholder workshops. Here, stakeholders from the European Commission, research institutes and business were interrogated on what key developments in policy, economy, society, technology, environment and geopolitics they expect in the decades to come. Inputs were elaborated using techniques inspired to the morphological analysis [30].
2. Translation of the overarching narrative into numerical assumptions to be fed into the modelling framework.

During the workshops held in step 1, stakeholders expressed interest in analysing two types of dynamics which could happen in the transition, either exclusively, or at the same time: 1) a case where the highest decarbonisation effort is taken on by energy carrier suppliers and large users (e.g. industries); 2) an opposite situation, where consumers engage in low-carbon choices, leading to emission reductions which initially leave policies behind. It is further decided to introduce a third type of situation, where these dynamics would likely have to happen together, rather than exclusively. This is the case where very ambitious decarbonisation targets are mandated. Detailed discussion on the pathway design process adopted is not in the scope of the paper. The matrix of dimensions and states for the three pathways (inspired to the final matrix obtained as output of the morphological approach) and the storyline built upon it are provided in Appendix.

The objective of this paper is to compare the implications of those pathways considering the cause-effect relationships between sectors to a low carbon society on the energy system. According to the trends above, the key features of the narratives for each pathway and the relative main assumptions are translated into modelling assumptions and summarised in Table 1 and Table 2. In this section, we explain how the pathways are translated to modelling assumptions specific to this study.

Consistent with the future defined in CL and LS pathways [29], the EU follows the coalition pattern to achieve the targets determined based on the Emission Trading Scheme (ETS). However, member states set country individual targets for sectors not included in the ETS (NON-ETS). Electricity, district heating and partly industrial process and energy emissions from energy-intensive industry sectors including oil refineries, steel works and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals as well as aviation are part of the ETS sectors; on the other hand, supply, residential, commercial, agriculture, rest of the transport as well as rest of the industry energy emissions are considered in the NON-ETS sectors. The assumptions behind the NON-ETS targets as well the country specific targets are given in the Appendix.

As the motivation for the CL pathway comes from the supply side and centralised transition, nuclear, gas and coal CCS options are given as mitigation options. 83% reduction for the ETS sectors is determined and non-ETS targets are defined according to country clusters given in Appendix. An additional, linearly increasing, decarbonisation target is set in the industry sector including energy and process related emissions for the ETS and NON-ETS sectors as a proxy for increased efforts by large consumers. Values for 2030 and 2050 for this target are shown in Table 2. These absolute bounds are converted to fixed reduction targets in the model. Additionally, the usage of heat pumps and residential solar heating is limited by restricting the share of ambient heat in the final energy consumption of residential sector to maximum 8% and the share of solar in the final energy consumption of the sector to maximum 5%. These restrictions are implemented to represent limited uptake of decentralised renewable options also in the residential sector, consistent with the storyline. A technology breakthrough in floating-platform offshore wind technology is also included in the technology assumptions, as deemed likely in stakeholder consultations summarised in Ref. [31]. Changes in heating and cooling degree-days due to climate change effect

Table 1
Summary of key modelling assumptions of the pathways [29].

	Coalitions for a Low carbon path (CL)	Local Solutions (LS)	Paris Agreement (PA)
Policy	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States;	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States;	95% decarbonisation target across all sectors in the EU as a whole by 2050, compared to 1990 levels
Environment	Changes in heating and cooling degree days computed assuming RCP4.5	Changes in heating and cooling degree days computed assuming RCP4.5	Changes in heating and cooling degree days computed assuming RCP2.6
Technology	**Large penetration of centralised renewable energy supply options** Limited penetration of solar thermals, heat pumps and renovation rate of buildings in residential sector; Breakthrough of floating platforms for offshore wind	**Uptake of low carbon technologies in households and road transport** Limited penetration of nuclear and CCS; Breakthrough of Building-Integrated PV;	**General strong recognition of the impacts of climate change** Breakthrough of Building Integrated PV; Breakthrough of floating for offshore wind Availability of CCS including BECSS
Sector Specific Assumptions	Higher push to decarbonisation of industrial processes-sector specific CO_2 reduction target is defined;	Higher decarbonisation of transportation and residential sectors-sector specific CO_2 reduction targets are defined;	

Table 2
Sectoral specific reduction targets of the pathways.

Pathway		CL	LS		PA
Sectors		Industry	Residential	Transport	N. A.
Milestone Targets CO_2 Emissions	2030	750 Mt	233 Mt	446 Mt	
	2050	295 Mt	60 Mt	80 Mt	

are assumed to be in line with RCP 4.5 and extracted from Ref. [32]. To reflect these changes, heating and cooling demands in the existing model structure are updated.

In the LS pathway, the push comes from society and the transition follows a more decentralised path. Therefore, the residential and transport sectors are assumed to contribute more to decarbonisation, compared to the CL pathway. This is in line with the logic that residential and transportation sectors are those where small consumers (e.g. citizens) make most of their consumption choices. ETS and NON-ETS targets are the same as in the CL pathway. The higher decarbonisation push in these sectors is again translated into fixed reduction targets specific to these sectors in the model, as can be seen in Table 2. The decarbonisation targets for industry assumed in the CL pathway are removed, instead. Nuclear and CCS deployments are not allowed. A technology breakthrough in building-integrated solar PV technology (also suggested as likely in stakeholder consultations [31]) is assumed. On the contrary, the breakthrough in off-shore wind is not assumed. Heating and cooling degree-days are computed according to RCP 4.5.

In the PA pathway, 95% emission reduction target across the sectors compared to 1990 by 2050 is assumed and the technology related assumptions of the CL and the LS pathways are partly combined. This translates from the storyline, which suggests that coordinated action from all users and sectors may be needed to achieve the ambitious decarbonisation targets. Additionally, to the conventional CCS technologies, BECCS option is also given as a CO2-negative mitigation option in the electricity sector. As the BECCS is able to capture the CO_2 from the atmosphere directly [2], the technology is modelled with the flexibility to capture the emissions not only from the electricity but also from the other sectors. The technology breakthroughs assumed separately in the CL and LS pathways are here considered together. That is, a breakthrough in floating-platform off-shore wind and building-integrated solar PV. Consistently, changes in heating and cooling degree-days in line with RCP2.6 are assumed and extracted from Ref. [32].

Finally, the following assumptions are common to all pathways:

- Techno-economic assumptions such as investment cost, variable costs, availability factors assumptions for solar PV, wind on-shore and off-shore, tidal and wave energy are taken from Ref. [31].
- The electric vehicles cost assumptions are developed according to the learning curve approach to calculate the cost of the battery packs in the vehicles. A learning rate of 16% is assumed, according to Ref. [33].
- The decommissioning curves of the existing nuclear power plants are determined based on [34].
- Energy efficiency technical measurements in industry are included as an option based on [17].
- Existing and forthcoming electricity exchange capacities are taken from Ref. [34].
- Livestock emissions are included in all the pathways based on [35]. Across all the pathways, it is assumed that the demand of the livestock in each country reduces by 50% until 2050 according to the study in Ref. [36].
- Fuel price assumptions are taken from Ref. [14].
- Heat saving processes and their potential in residential buildings are included according to Ref. [37].
- End-use demand assumptions are derived based on the socio-economic path in terms of GDP and population defined in the EU Reference scenario [18] and adopted via the linkage with NEWAGE.

4. Integrated scenario analyses

This section compares three pathways, defined in Section 3, to analyse the energy transition in the EU28. The analysis starts with power system, follows with the comparison in the sectoral developments, and assessment externalities in different pathways. The section ends with the discussion including comparison of some of the findings with the latest scenario analysis carried out in Ref. [2].

4.1. Power system

The electricity capacity as well as electricity generation increase in all the pathways. The highest capacity and generation are observed in PA pathway. This can be explained with the highest level of electrification required due to the highest reduction target. The electricity capacity almost doubles until 2050 across the pathways and generation capacity increases by at least 30%. The reduction targets in the three pathways do not differ significantly until 2030 and the technology assumptions do not diverge. Therefore, the main differences in the transition pathways are seen after 2030.

LS pathway represents a transition driven by consumers. Therefore, the system moves towards to decentralised generation options such as building-integrated solar PV. Together with onshore wind, it compensates the generation from nuclear and CCS power plants in the other pathways. However, LS pathway shows the lowest generation level in

2050, despite the higher installed capacity compared to CL pathway. This can be explained with the lower full load hours of the decentralised technologies compared to centralised technologies, as well as the required back-up capacity with the increasing share of renewable generation in the system. In line with the above, although the capacity of natural gas slightly increases after 2020 (Fig. 7), the generation from this energy carrier constantly decreases in all the pathways (Fig. 8). In LS pathway, gas power plants generate more compared to other two pathways to compensate the generation from CCS technologies.

Due to the expected higher cost reductions in off-shore wind technology, offshore wind becomes quite competitive with onshore wind. Additionally, a breakthrough in floating offshore wind is assumed in the CL and PA pathways. The availability factor of this technology is higher, due to the higher availability of the resource off the coast compared to on-shore. With this competitive advantage, offshore wind has relatively higher diffusion and it is chosen over onshore wind and solar technologies especially after 2030 as a mitigation technology. This is seen in Figs. 7 and 8. The highest share of biomass is in the PA pathway in the electricity generation as well as in the capacity mix due to the deployment of BECCS technology.

According to Ref. [38], the overall renewable target in the final energy consumption in 2030 set by EU is translated as 57% share of renewables in power sector. This target is not given as a binding constraint in any of the pathways to give more flexibility to the model across the sectoral targets. It is achieved only in the PA pathway thanks to the early deployment of high shares of offshore wind.

4.2. Development in the end-users

In this section, we compare end-user's developments in the three pathways and analyse the interactions between sectors, as this has been a short-coming in recent literature based on our best knowledge so far for the reduction targets studied in this paper.

In industry, the share of biomass products is lower in 2050 in PA pathway compared to LS and CL pathways, as can be seen in Fig. 9. Due to the additional decarbonisation target in the industry in CL pathway, highest electrification and highest share of biomass are observed in this pathway for this sector. Although the decarbonisation target is pushed even more in the PA pathway, the lowest share of biomass products is seen in this pathway in the industry as most of the biomass potential is utilised in the electricity sector (Figs. 7 and 8).

The shares of the energy carrier change in the final energy consumption of industry in 2050 in comparison to 2015 (Fig. 9). However, CO_2 emission reductions are limited (Fig. 10). With the additional target in CL pathway, the sector is pushed already at the limits. Therefore, the level of the emissions in CL and PA pathways follows a similar trend. Some of the industry branches such as iron and steel, other chemicals, other non-metallic minerals, other industries, food and tobacco are able to decarbonise to a certain degree with the available mitigation technologies. On the other hand, sub-sectors such as lime, cement and ammonia follow the same path that they have in 2015 also in 2050, as can be seen in Fig. 10. The emissions in Fig. 10 do not include the emissions from auto-production CHP plants. It might be worth to have a closer look at iron and steel emissions. Although, certain measures are implemented such as application of bio coke to produce the blast furnace slag in our model, it is only possible to decarbonise this subsector to a certain degree. The coal is still required in the finishing process. This explains why the share of coal slightly decreases but does not disappear in all the pathways despite the ambitious reduction targets. In LS pathway, the lowest electricity share is seen. As the electricity generation has the lowest value in this pathway (Fig. 8) compared to others, the impact of this is seen here. As there is no additional push to the decarbonisation of industry is assumed, the share of gas experiences a smaller decrease in the energy balance compared to the other pathways.

The effect of the availability of BECCS is seen in Fig. 9 as well. In PA pathway, BECCS is modelled as a technology which can be deployed in the electricity but can also capture the emissions from other sectors. Therefore, in this pathway the share of biomass is lower in the industry as most of the available biomass in the system is utilised in the electricity sector to produce negative emissions; on the other hand, priority in the use of biomass is given to industry in CL pathway, due to the push assumed for this sector. Through the biomass usage, it is possible in CL pathway to decarbonise the sector to a certain degree without applying the energy efficiency measures.

The reduction of the final energy consumption in the residential sector reaches around 25% in all the pathways. The renovation of the building stock and the replacement of old space heating technologies with new ones contribute to this decline. Until 2040, slow phase out of oil boilers is seen. With the integration of health damage costs in the optimisation function, early phase out of coal takes place in all the pathways, as seen in Fig. 11. As a result of the additional reduction target in the LS pathway and overall high reduction target in PA

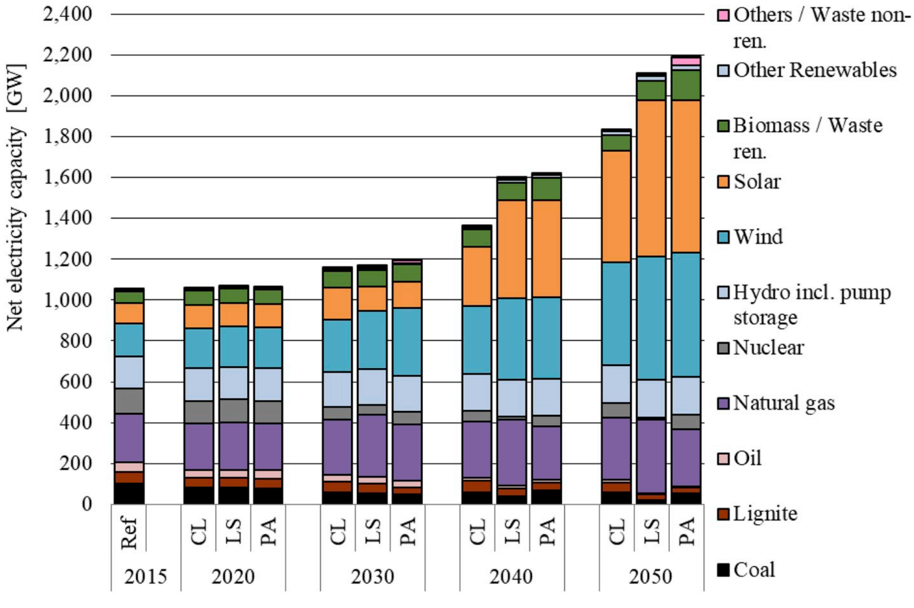

Fig. 7. Pathway comparison of the installed electricity generation capacity in the EU28.

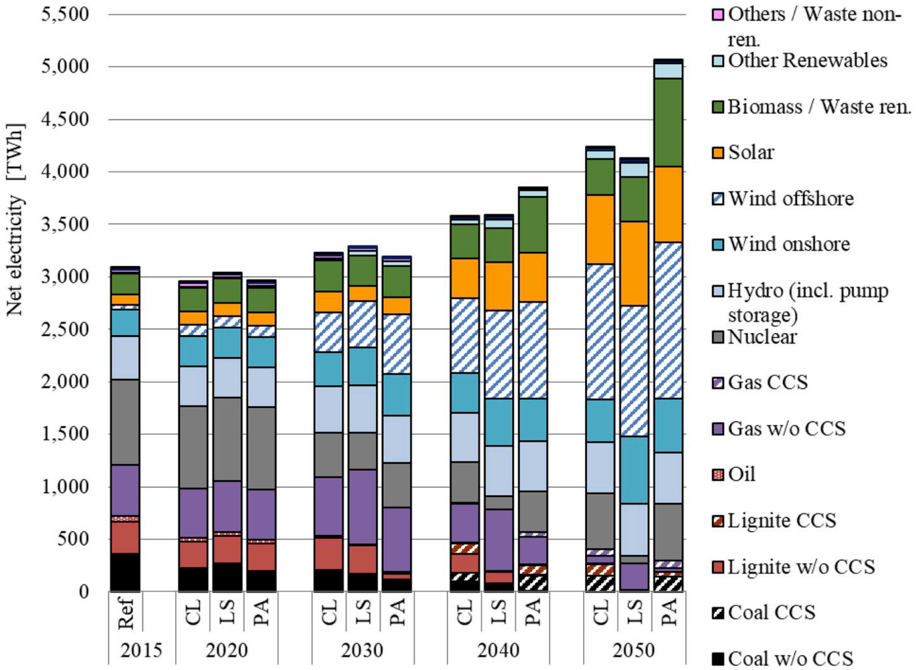

Fig. 8. Pathway comparison of the net electricity generation in the EU28.

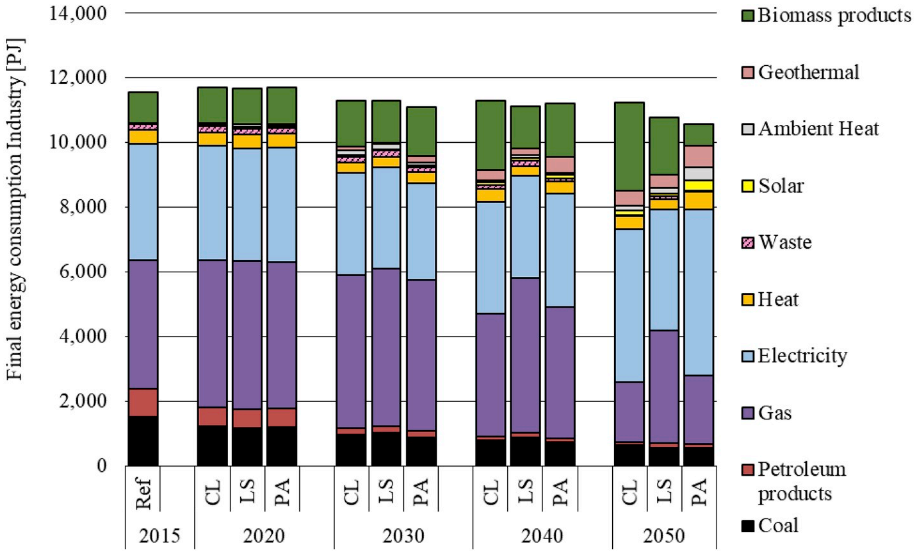

Fig. 9. Pathway comparison of final energy consumption industry in the EU28.

pathway, the energy mix varies between the pathways. The main differences between the CL and LS pathways come from the level of gas, ambient heat, solar as well as heat from district heating. When the residential sector follows more centralised applications (CL pathway), gas and heat coming from district heating plants with the deployment of coal and lignite CHPs with CCS (Fig. 7) play important roles in the final energy consumption. On the other hand, when the decarbonisation of the residential sector comes mainly from end-users (LS pathway), ambient heat and solar increase their shares as a result of the deployment of the heat pumps and solar thermal technologies to provide space heating and hot water. The share of gas reduces to 7% in PA pathway. The share of biomass decreases in all the pathways since its potential is mainly exploited in other sectors. Its share is taken over by different energy carriers in different pathways. In CL pathway, the role of biomass is mainly compensated with district heating as the trend in the pathway is more centralised applications. However, solar heaters and heat pumps compensate biomass use and district heating in LS pathway in the final mix. The energy mix has some differences between LS and PA pathways as well. This means that it is still possible to push the sector a bit further with higher deployment of heat pumps for higher decarbonisation. In PA pathway, a slightly higher share of electricity and a higher share of ambient heat is seen in Fig. 11 compared to LS pathway. The energy transition requires higher electrification in the residential sector as well.

As the responsible country for the international aviation and navigation emissions is not always clear [2], we distinguish the final energy consumption for these transport services from the domestic ones to have a better understanding. Therefore, their CO_2 emissions are also not included in Fig. 13. The final energy consumption of the transport sector (Fig. 12) follows a similar trend as in the residential sector (Fig. 13). The energy consumption decreases by 2050 around 30% in all the pathways

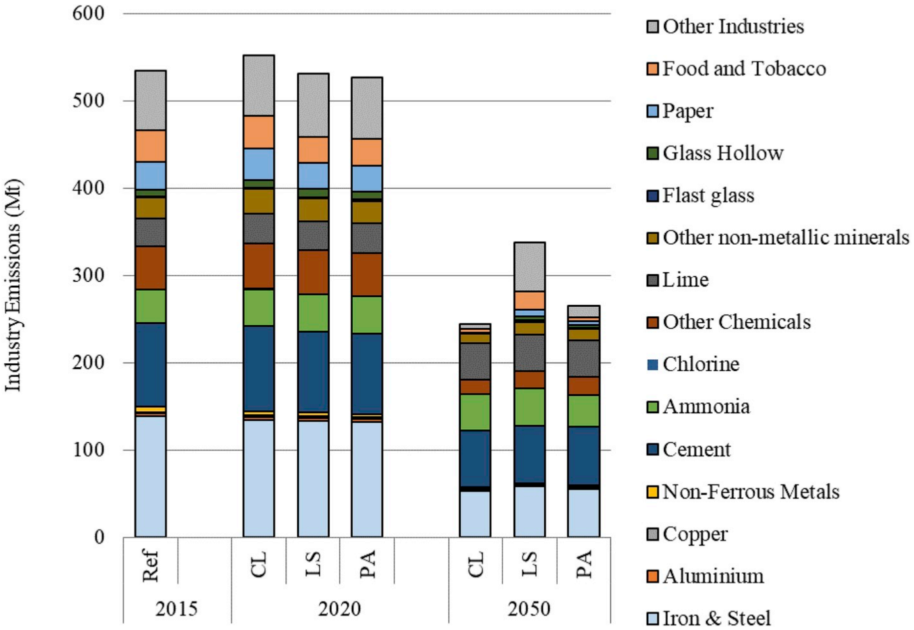

Fig. 10. Pathway comparison of industry emissions (without emissions from auto-production CHP plants) in the EU28.

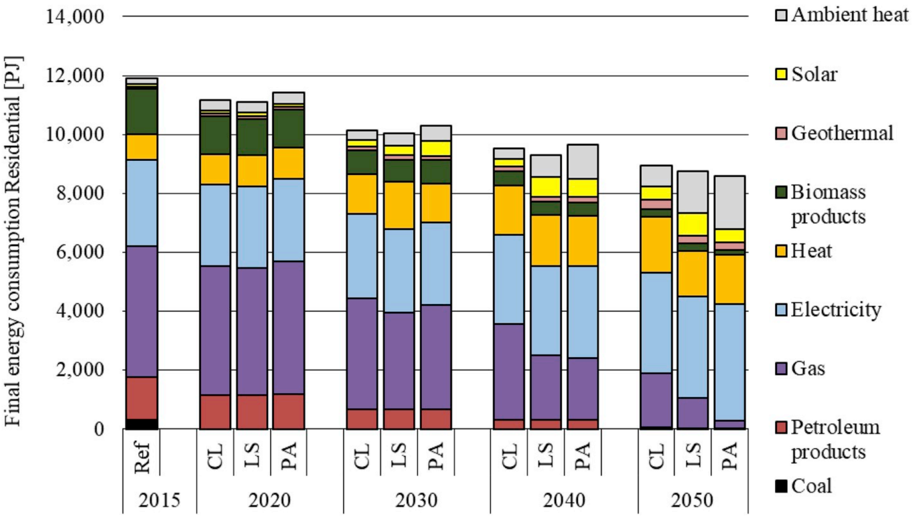

Fig. 11. Pathway comparison of final energy consumption residential in the EU28.

with the replacement of old cars and trucks as well as with the efficiency improvements in aviation for the domestic services. The share of petroleum products in transport also decreases for the domestic transport services. As seen in Fig. 13, domestic aviation and navigation can be almost fully decarbonised with biofuels and hybrid technologies starting from 2040. Without additional targets, the CO_2 reduction from the road transport is rather limited in CL pathway. This means that a share of petroleum products in the energy mix, such as diesel and gasoline, comes from car transport in CL pathway (Fig. 12). Along with the expected cost reduction of electric vehicles, the share of electricity grows in all the pathways. In CL pathway, the level of electrification stays rather limited compared to LS and PA pathways. The share of biofuels also increases in all the scenarios. Comparing the share of biofuels between the pathways highlights the importance of biomass and its utilisation. The highest share of biofuels is observed in LS because the decarbonisation of this sector becomes crucial when aiming higher decarbonisation in the sector. On the other hand, the share of biofuels is lower in PA pathway compared to LS since biomass potential is mainly utilised in electricity, as mentioned before. In LS and PA pathways, a small share of hydrogen is also observed starting from 2040 (Fig. 12). This hydrogen is used as fuel in heavy duty trucks and in domestic aviation. Especially in PA pathway, the full decarbonisation of road transport might be expected. However, the reduction of CO_2 emissions is around 90% for the car transport and around 90% for the freight-heavy duty. The reason for the residual emissions in these modes lies in the remaining stocks of the vehicles deployed in previous years. Furthermore, there are special-purpose vehicles such as construction site or emergency vehicles. Small share of these applications might still work with conventional fuels due to their required availability. The highest electrification in transport is seen in PA pathway with the lowest final energy consumption for the sectors. This also explains the higher efficiency of the EVs and their higher deployment also brings energy efficiency improvements.

As a last figure in this section, the total final energy consumption across the sectors is given (Fig. 14). As the total final energy consumption in different sectors decreases, the reductions in all the pathways are

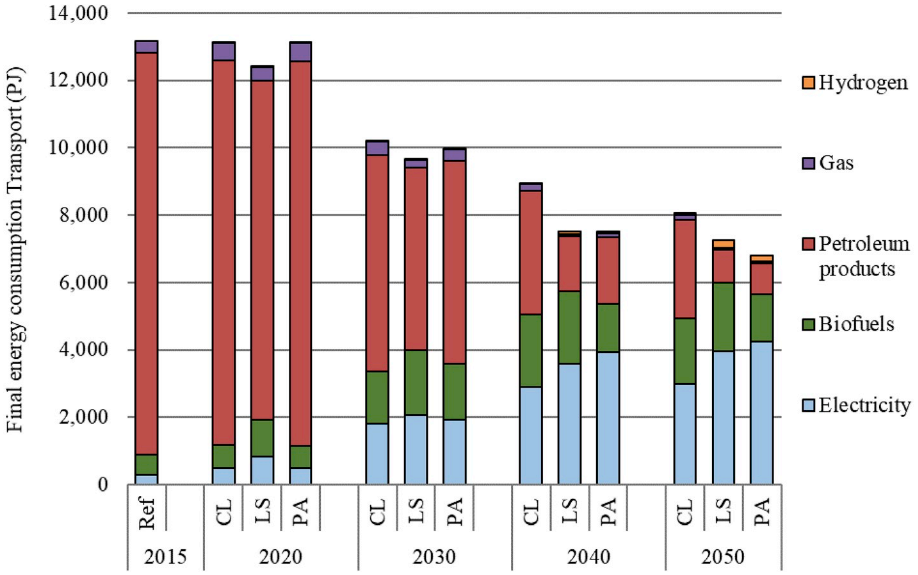

Fig. 12. Pathway comparison of final energy consumption transport (without international aviation and navigation) in the EU28.

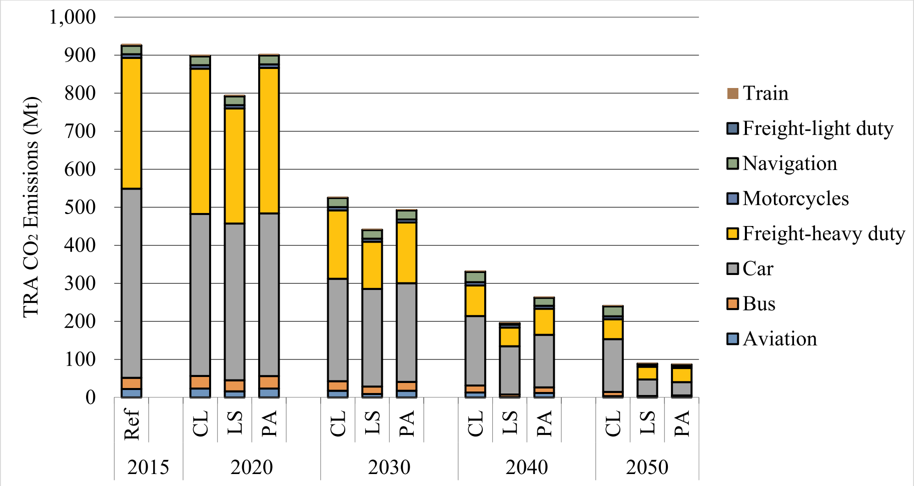

Fig. 13. Pathway comparison of transport emissions (without international aviation and navigation) in the EU28.

also seen (Fig. 14). The total final energy consumption decreases in all the pathways between 23 and 30%. The highest decrease is observed in PA pathway, due to the highest deployment of energy efficiency measures. These efficiency measures also help the system to achieve a stronger reduction target compared to the other two pathways. Despite the decreasing total final energy consumption, the share of electricity increases constantly; on the contrary, the share of petroleum products decreases over time from 50% to 3% in PA pathway and to 14% in CL pathway similar to the developments in the individual sectors. The amount of electricity shown in Fig. 14 in all the pathways is lower compared to the generation in Fig. 8. This explains that in some of it is used in the conversion processes for district heating or to produce hydrogen. However, the majority of electricity is directly used in the end users (Figs. 9, Figs. 11 and 12).

4.3. *Externalities*

Including health damage costs and ambitious GHG-mitigation targets reduces the level of other emissions (Fig. 15). With the introduction of the damage costs already in 2020, sharp decreases are seen in SO_2 and NO_X emissions, with the coal phase out in the residential sector. PM_{10} and $PM_{2.5}$ emissions also experience reductions along with the decarbonisation of the whole system. It is important to point out that, as explained in section 2.1.1, only half of the actual damage cost values are introduced in 2020. When the full costs are considered, the co-benefits of decarbonisation of the system might be expected to be even higher in this year.

Reductions of SO_2 emissions halt already in 2020 because of the non-mitigatable emissions coming from the industrial processes such as other non-ferrous metal production. Additionally, since the demand for industrial branches is increasing and therefore process emissions, it is not possible to mitigate the emissions further in this sector. On the contrary, slight increases are observed in all the pathways. The transport sector also contributes to the reductions between 2015 and 2020 with the introduction of the damage costs in the system. The reason for reductions of SO_2 in transport is mainly fuel switching in navigation from heavy fuel oil to diesel and LNG. This change in the transport sector also contributes to the reductions in $PM_{2.5}$ and PM_{10} emissions.

NO_X emissions are decreased up to 70% of their initial level after 2020 with the highest reduction in PA pathway, which is in line with the highest decarbonisation target. VOC emissions experience higher reduction especially after 2040 in PA pathway compared to the other

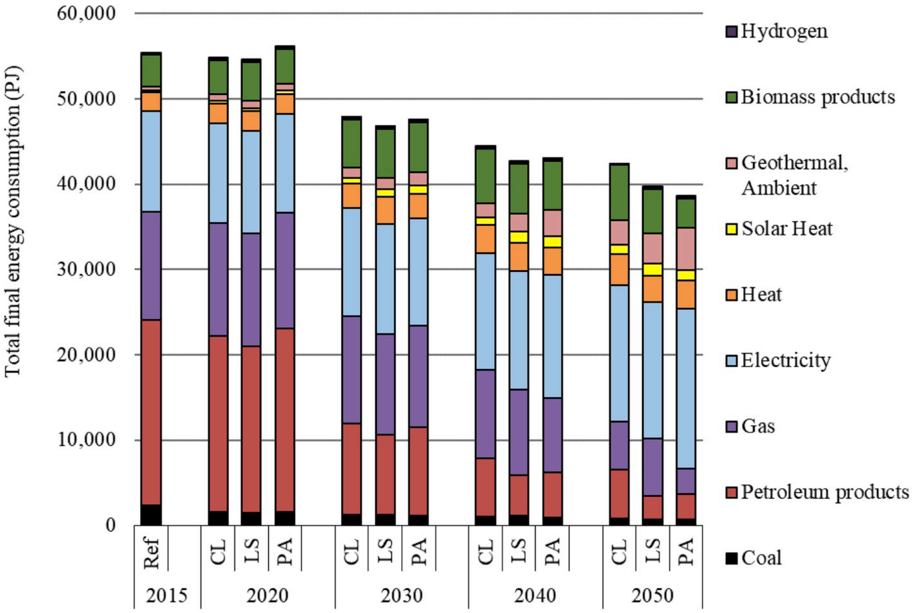

Fig. 14. Pathway comparison of final energy consumption in the EU28.

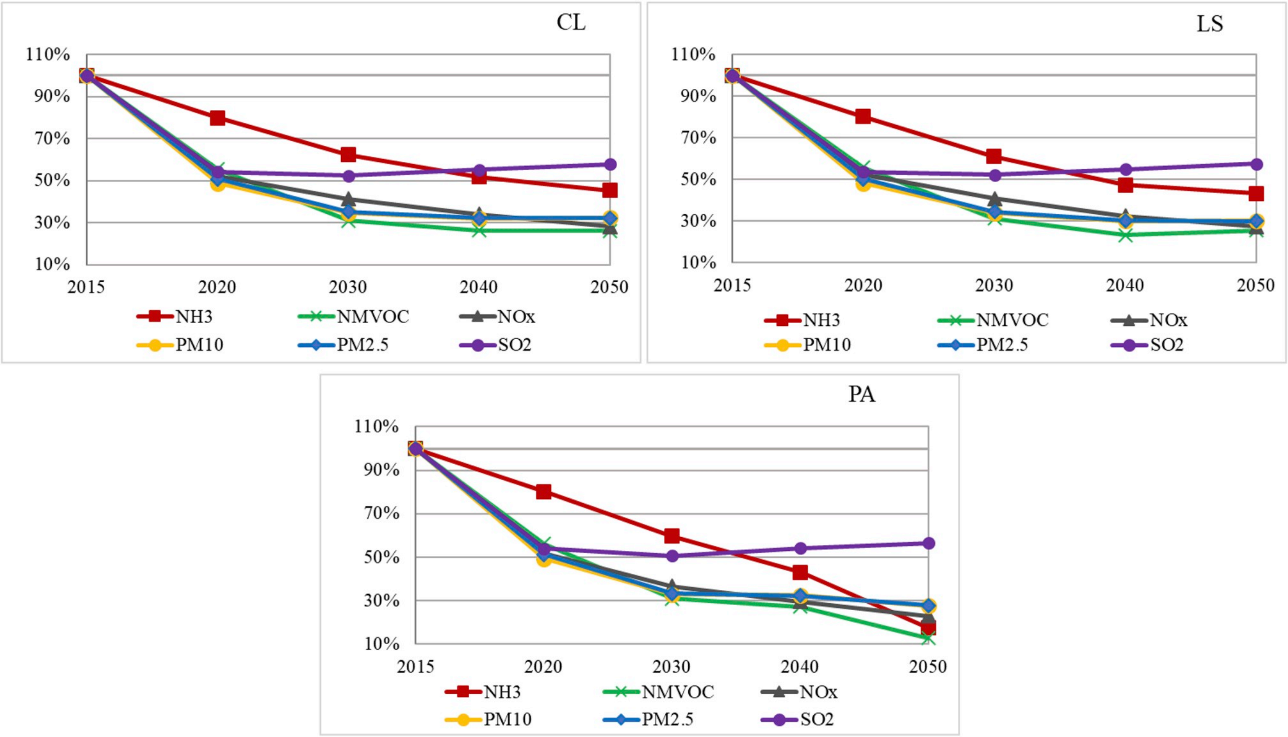

Fig. 15. Emission reductions of air pollutants relative to 2015 levels in the EU28 (excluding international aviation and navigation).

two pathways. The reason is mainly the lower share of biomass in agriculture in the energy mix as most of the biomass potential is utilised in the electricity sector in this pathway. This also explains the reduction of NH_3 emissions. Additionally, the differences between PA and other pathways for the NH_3 emissions in 2050 are mainly caused by the industry. On the other hand, industry experiences the highest level of electrification in PA pathway which also helps to reduce the pollutant levels further. In electricity supply, the decommissioning of the existing coal power plants is one of the main drivers for the reductions of the pollutants.

4.4. Discussion

In this study, we have analysed different deep decarbonisation pathways for the EU energy system taking into account the externalities, macro-economic feedback of the transition and the potential role of technology innovations. In this chapter, we discuss the outcomes and compare some of the results and insights concluded in the study with the latest scenario analyses delivered in Ref. [2] since this is the only identified study in recent literature that provides a comparable deep analysis of the energy system transition but without considering possible feedbacks from externalities such as air pollution and macro-economic variables as delivered by a CGE model.

According to our results, in the overall energy mix, electricity becomes the dominant energy carrier across all the pathways. In PA pathway, it reaches 43% of final energy consumption, which is slightly lower compared to scenario analyses for 90% and 100% reduction targets in Ref. [2]. On the other hand, in PA results, the share of geothermal and ambient heat is 12%, which is higher compared to the results in Ref. [2] for the same energy carriers. Especially in residential and commercial sectors, these carriers could play an important role in the transition in addition to electricity. The share of electricity in the other pathways is almost equally important, reaching 38% in CL pathway and 40% in LS pathway. The increase in the share of electricity depends on which sectors do most in the decarbonisation process. Due to the additional reduction targets in industry in CL pathway, the share increases to 42% in 2050, while this share is rather low in LS pathway. In PA pathway, the level of electrification is highest, with 49% in the industry. In LS pathway, where a push to decarbonisation comes from residential and transport, higher shares of electricity are observed in final energy consumption by these two sectors compared to CL pathway. They amount to 38% and 31% respectively. This provides a detailed sectoral insight on how high decarbonisation targets may turn into electrification of different sectors. These insights complement those given in Ref. [2].

The energy system is expected to experience a high level of electrification. According to the analysis in this paper, wind energy becomes a dominant technology with the capacity deployment increasing particularly after 2030. The cost reduction especially on the offshore wind might determine the trend for this technology. In all the pathways, the share of the technology in the electricity generation consistently increases between 40% and 45% in 2050 considering both onshore and offshore deployments. Based on the foreseen higher capacity factors of offshore wind, it is expected to take a higher share than onshore. The role of wind technology is mentioned in different scenarios carried out in Ref. [2] with similar figures. Similar trends are also expected with solar PV. A sharp cost reduction in building-integrated solar PV can significantly impact the deployment of solar technologies in the residential sector. Although the contribution of solar technologies to the electricity generation mix is higher in PA and LS pathways, it does also play an important role in CL pathway. In the electricity sector, we follow a rather different path in the LS pathway unlike the scenarios compared in Ref. [2]. The possibility of a decentralised energy transition without nuclear and CCS technologies is investigated. In LS pathway, the share of nuclear in the electricity mix decreases to 1.7% in 2050 as a result of the new capacity deployment restriction imposed in the model. 80% reduction of GHG emissions is still possible with the help of a breakthrough in solar PV, other decentralised technology options in other parts of the energy system such as heat pumps or solar heaters, and higher deployment of EVs in transport sector. Electricity generation is lower compared to the other two pathways, mainly due to lower full load hours of renewables compared to CCS and nuclear. When nuclear capacity deployment is not restricted, in the CL and PA pathways, it still plays a role in the power sector with the share of 12% and 10%, respectively. These findings are in line with the scenario analyses in Ref. [2].

Additionally, the different renewable technologies increase their share in the energy mix in all the pathways. In 2015, the share of renewables is only 9% in industrial energy consumption. This share rises to 31% in CL pathway in 2050. The limited share of renewables in residential in 2015 rises to 31% in the LS and PA pathways in 2050. The additional technologies which can utilise geothermal such as ground heat pumps in the residential sector or increased use of electricity heat pumps further to solar thermal applications gain a share in the residential energy mix. These energy carriers also play a role for the decarbonisation of industry. The share of biofuels in 2050 increases in transport in all the pathways. The biofuels are not only used in the car transport but also defined as an option in the international modes such as aviation and navigation. They currently lack mitigation technologies and this makes it more challenging to project their future state. In our analysis, we have concluded that if the milestones targets for the further technology developments are achieved according to Ref. [19], increased share of renewables from biofuels will be observed in this sector along with the reduced emissions from these transport modes.

In our study, biomass stands out as a mitigation option. It can be applied in different parts of the energy system. For example, to achieve beyond 80% reduction, CCS has an evident role running on biomass in PA pathway. To offset especially the remaining emissions from other industries, around 100 GW BECCS capacity deployment is seen in this pathway. On the other hand, the highest share of biomass is recorded in CL pathway in the industry. The transport sector also requires biomass for biofuels. The demand for biofuels increases again with the decarbonisation level of the sector. The highest share of biomass in transportation is observed in LS pathway, due to the more stringent emission targets we imposed for the sector.

In the PA pathway, where 95% reduction of GHG emissions is achieved, the availability of CCS technology plays an important role; not only running on biomass but also on other fuels. The technology can still provide the base load demand but also offers a solution for the CO_2 generated by the use of fossil fuels. In Ref. [2], the role of CCS in many decarbonisation scenarios is also emphasized. According to our results, the share of natural gas decreases from 22% in 2015 in the final energy consumption to 12% in CL, 15% in LS and 7% in PA. However, we do not observe any mid-term reductions until 2030. The expected reductions also follow similar trends with the latest scenario analysis in Ref. [2]. It has to be noted that in the latter, more ambitious reductions are seen especially in 2050. This can be partly attributed to the consideration of e-gas options which are not currently part of our model.

The impacts of energy efficiency measures are observed in the declining final energy consumption. Compared to 2015, a decrease between 23% and 31% is observed across the pathways. The measures are applied at the highest level in PA pathway to achieve a higher reduction target. Although energy demand in industry increases across the different subsectors, the constant level of the final energy consumption shows that improvements come from higher efficiency machinery and other measures. The final energy consumption figures in residential and transport are also influenced by energy efficiency measures, experiencing a constant decrease. The highest savings in transportation and residential are seen in PA pathway. With the replacement of old gasoline cars with electric cars and old trucks with more efficient vehicles, a 19%–29% decline in energy consumption is achieved. Similarly, the replacement of old gas and oil boilers with the more efficient boilers and heat pumps helps reduce the energy consumption in the residential sector. The demolishment of old buildings and application of renovation measures for the remaining stock of existing buildings also contributes to the decrease in residential energy demand.

We have also assessed the synergies with air pollution control and GHG reduction targets in our study. The introduction of the pollutants and their damage costs in the system accelerate the coal phase out in some of the sectors such as residential and optimises the biomass usage considering the pollutants caused in the burning process. Across the three pathways, NO_x, VOC, $PM_{2.5}$, PM_{10} emissions follow similar reduction paths reaching between 60% and 70% reduction compared to 2015.

5. Conclusion and outlook

With this study, we have provided the ground work for one of the main messages on the decarbonisation of the EU energy system from the REEEM project [28]: among the technology trends, sectoral integration, energy efficiency and electrification of transportation consistently confirmed as potential enablers of the decarbonisation based on the energy system analyses. We have added detailed system-focused analyses with insights into cross-sectoral dynamics, considering externalities and macro-economic variations in the energy system. In this section, we aim to draw further policy-related conclusions which could help policy makers during the design of the energy system for the energy transition.

We have assessed three pathways: in the first pathway, it is assumed that the effort mainly comes from the energy supply for decarbonisation. In the second one, consumers take more active role and the system becomes demand-driven and in the last one 95% reduction is explored. Our findings show us that 80% reduction is feasible, both where supply-side and demand-side options prevail. 95% reduction is possible with domestic sources in the EU28 with the application of BECCS. Our findings show that the energy mix in different sectors differ significantly between pathways. Therefore, to achieve a certain GHG reduction target, it is important to determine the potential dynamics and trends in the energy system especially regarding potential for sectoral integration and for broader engagement in the society.

Higher electricity share in each part of the system is seen in the energy mix in all the pathways. Electrification will be one of the enablers to achieve the transition not only for one specific sector but in the entire energy system. Higher electricity generation from renewables will be a prerequisite for higher electrification. The need for flexibility options will also rise. This need should be further analysed in a grid dispatch model to verify the grid stability. Further infrastructure development will be necessary with the higher electricity generation in the system and electrification of different sectors. The required infrastructure might also delay the transition. On the other hand, other energy carriers such as ambient heat and geothermal will also have their roles in the energy transition in different paths of the energy system.

We also conclude that especially in the power system, natural gas continues to contribute as a mean to increase security of energy supply as a back-up option. A separate market instrument for those capacities might be introduced. Another important aspect is the state of the existing gas grids. It is clear in our study as well as in the similar ones, that its share will be decreasing over the time. Therefore, how to utilise the existing gas infrastructure in the future should already be investigated. Based on our findings, the share of coal in the energy mix decreases. It might still play a limited role in the electricity mix only when CCS technology is considered as seen in the CL and PA pathways. The results in LS pathways show that an electricity mix without any coal-based generation is also achievable in 2050.

In each pathway, certain reductions in the final energy consumption figures of the different sectors will be experienced, although the demands are expected to increase. Energy efficiency measures will also play a key role in the energy transition. Therefore, it will be also important not only to invest on the new technology developments but also on efficiency measures for the existing technologies and processes in the energy system.

To achieve the energy transition and decarbonisation beyond 80%, further technology developments are necessary especially with CCS, building integrated PV and offshore wind. Biomass and other types of CCS technologies should become commercially available latest in 2035 to achieve the reduction targets beyond 80%. Social acceptance problems need to be also addressed. With the current modelling applications, it is challenging to take into account issues such as public acceptance or availability of land for the new technologies. Stronger policy decisions might be required to support the technology development. For the zero-net emissions, alternative mitigation approaches e.g. nature-based solutions will be necessary and the projections for the new technologies about their availability and techno-economic characteristics need to be communicated with the research community.

Biomass will be one of the key elements in the energy transition and the utilisation of the source can induce additional emission reductions in different parts of the energy system. Therefore, it will be also essential to have required infrastructure development and also develop new business models for the transportation and production of energy vectors such as biodiesel and bio kerosene. This brings up again the need for broader engagement in the energy transition and the significance of sector coupling. Drivers in one sector can directly impact the transition of the other sector.

Air pollution control benefits from the transition towards to a low carbon energy system and vice versa. The use of biomass for some applications such as BECCS becomes critical with regard to air pollution control and related damage costs. Therefore, the cause-effect relationships also need to be considered in this part of the energy system.

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Appendix

A. Pathway Assumptions

A.1. Common assumptions on policy for Coalitions for a low carbon path and Local solutions pathways

Table 1
CO_2 emission targets by EU Member State: Coalitions.

	Targets for 2020 (compared to 2005)	Targets for 2030 (compared to 2005)	Target for 2050 (compared to 2005)
EU-28 ETS	**−21%**	**−43%**	**−83%**
	Effort sharing decision (ESD)	Effort sharing decision (ESD)	Effort sharing decision (ESD)
France	−14%	−37%	−80%
Portugal	1%	−17%	−80%
Spain	−10%	−26%	−80%
Italy	−13%	−33%	−80%
United Kingdom	−16%	−37%	−80%
Germany	−14%	−38%	−80%
Netherlands	−16%	−36%	−80%
Belgium	−15%	−35%	−80%
Luxembourg	−20%	−40%	−80%
Austria	−16%	−36%	−80%
Denmark	−20%	−39%	−80%
Sweden	−17%	−40%	−80%

(continued on next page)

Table 1 (*continued*)

	Targets for 2020 (compared to 2005)	Targets for 2030 (compared to 2005)	Target for 2050 (compared to 2005)
Finland	−16%	−39%	−80%
Ireland	−20%	−30%	−80%
Poland	14%	−7%	−50%
Czech Republic	9%	−14%	−50%
Bulgaria	20%	0%	−60%
Romania	19%	−2%	−60%
Estonia	11%	−13%	−60%
Latvia	17%	−6%	−60%
Lithuania	15%	−9%	−60%
Croatia	11%	−7%	−60%
Hungary	10%	−7%	−60%
Greece	−4%	−16%	−60%
Slovakia	13%	−12%	−60%
Slovenia	4%	−15%	−60%
Cyprus	−5%	−24%	−60%
Malta	5%	−19%	−60%
EU-28 non-ETS	**−9%**	**−30%**	**−75%**

The utilised criteria to define the emission reduction targets in 2050 (by Member States clusters) are:

- **Geographical location:** Countries located near each other have several similarities that could encourage a partnership and the pursuit of similar environmental objectives. They typically use similar, if not identical, languages, have comparable wind and sun resources and stronger commercial partnerships, thus facilitating potential cooperation around a common environmental goal.
- **Wind and sun availability:** Wind and solar, more specifically PV, are the fastest growing technologies in terms of installed capacity. Although the installed capacity for hydro power is still larger than wind and PV, as for 2016 [39], its growth potential is much more limited due to the uneven geographical distribution of its resources.
- **Economic situation:** When coming to economic terms, the term “optimal solution” comes inevitably in mind, however, installing and utilising energy from renewable sources may not always be the cost optimal scenario (at least when costs due to environmental and public health damages are not internalised in the objective equation). Additionally, on a deregulated energy market the consumers are the ones who chose where their energy comes from, so the market is subject to their preferences, which is a parameter rather difficult to quantify. Therefore, the economic situation will be used here as proxy of the willingness of a certain country to invest, or not, on renewables, as it, ultimately, represents the country’s potential to invest on this technology.
- **Coal resources:** Around every political decision there are economic interests from different groups and with the coal companies it is not different. Coal was specifically chosen as it is still the fossil fuel more broadly utilised as primary energy source in Europe in 2015 (Coal: 144874, Crude oil: 69144, Gas: 111117. All in ktons of oil equivalent [40]. This criterion helps identifying possible economic interests in favour of the coal industry.

Effort Sharing Decision: The Effort Sharing Regulation adopted on May 14th’ 2018 [41] sets Member State GHGs emission reduction targets. These targets concern emissions from most sectors outside not included in the EU Emissions trading system, such as transport, building, agriculture and waste.

Clusters.

a. Green (or “Clean”) is optimal
  - **Members:** France, Portugal, Spain, Italy, United Kingdom, Austria
  - **Rationale:** For this group of countries, due to the availability of resources, the optimal solution is to utilise energy from renewable or cleaner sources. Additionally, Spain, Portugal and Italy have quite good access to natural gas due to proximity to North Africa and LNG terminals, while France has already a relatively large clean energy supply due to its installed capacity of nuclear power plants.
  - Non-ETS targets: Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

b. Politically and economically aligned
  - **Members:** Germany, Netherlands, Belgium, Luxembourg
  - Rationale: This group of countries has good or very good economic situation, a history of working together and similar wind and solar resources availability. All the countries, except for Luxembourg, have access to the North Sea, which indicates their high off-shore wind potential. Although Germany has one of the largest resources of coal in Europe and still depends heavily on it, its economic force and recent environmental efforts indicate that it is following the path in favour of more ambitious environmental targets.
  - Non-**ETS targets:** Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

c. Politically and economically aligned – the Nordic league
  - **Members:** Denmark, Sweden, Finland, Ireland
  - **Rationale:**This group could also be a part of group “b” depending on the application. Although this group can be further divided into the old EU-members (Denmark, Sweden and Finland), who have similar economic situation and higher GDP per capita, and the new EU-members (Estonia, Latvia and Lithuania), it also presents several similarities that justify this composition. Starting with the geographical location, resulting into similar access to wind and solar resources and similar challenges regarding the impacts of climate change. Second there is the share of petroleum products and renewables on the gross inland energy consumption, which in 2015 represented more than 55% for every member of the group, except for Estonia. Finally, none of the countries in this group have considerable coal mines.
  - Non-ETS targets: Higher reduction than the EU target of 75% for non-ETS by 2050: 80%.

d. Coal for the economy
  - **Members:** Poland, Czech Republic
  - Rationale:Both Poland and Czech Republic are large producers of coal in Europe and extensively utilise this resource inside their borders, as it represents 39% of the gross inland energy consumption of Czech Republic in 2015 and 51% of Poland's in the same year. Any limitation to the use of coal would have consequences in these two countries.
  - Non-ETS targets: Much lower reduction than the EU target of 75% for non-ETS by 2050: 50%.

e. The cheapest way
  - **Members:** Bulgaria, Romania, Estonia, Latvia, Lithuania, Croatia, Hungary, Greece, Slovakia, Slovenia, Cyprus, Malta
  - **Rationale:** Although this group presents some economic disparities, it presents homogeneous characteristics in terms of access to solar and wind resources. Due to the economic condition of most members, this group depends heavily on the cost reduction of the renewable energy technologies in order to be able to fully deploy them and will most likely apply the cheapest option in regards to energy generation. They also have relatively easy access to both gas, due to proximity with Russia, and coal, due to proximity with Poland and Czech Republic, so cost will play an important role on the environmental ambitions of this group.
  - Non-ETS targets: Lower reduction than the EU target of 75% for non-ETS by 2050: 60%.

A.2. Common assumptions on the Global setting for Coalitions for a low carbon path and Local solutions pathways

Table 2
CO_2 emission targets in regions outside the EU [29].

Region	CO_2 emission targets in 2050	Rationale
USA	Halfway between 2 °C target and current policies	Despite Trump's presidency, an expressive number of an expressive number of states, cities, tribes, universities and business, including the states of New York and California, signed an open letter confirming their support to the Paris Agreement.
China	2 °C target	Although it does not have high GDP per capita, as EU or the USA, its economy is growing fast and it is also home to 7 of the 10 largest photovoltaic cell manufacturers and 4 of the top 10 wind turbine manufacturers.
Japan	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but its current high dependency on fossil fuels and lack of resources would undermine its willingness to pursue the 2 °C target
Republic of Korea	2 °C target	Part of OECD, high GDP per capita and HDI. Wouldn't have opposition to pursue the 2 °C target
Canada	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but as its economy also depends on production of oil, it is possible that they do not follow the 2 °C target
Mexico	Halfway between 2 °C target and current policies	Part of OECD, medium GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, as this ambition has already been shown through the creation of a long-term strategy to reduce emissions. However, due to its economy, it might end up not following the reduction cuts necessary for the 2 °C target
Australia	Halfway between 2 °C target and current policies	Part of OECD, high GDP per capita and HDI. Would seek a higher ambition reduction target than the current policies, but as its economy also depends on production of oil, it is possible that they do not follow the 2 °C target
Norway	80% reduction compared to 1990 levels	Would seek similar target to the EU's as it is also part of the EU ETS and an important partner
Switzerland	80% reduction compared to 1990 levels	Would seek similar target to the EU's as they signed an agreement in 2017 to link their emissions trading systems
New Zealand	2 °C target	Part of OECD, high GDP per capita and HDI. Wouldn't have opposition to pursue the 2 °C target
Iceland	2 °C target	Would seek similar target to the EU's as it is also part of the EU ETS

A.3. Detailed assumptions for the Coalitions for a low carbon

Economy: '*Growth at different speeds'*

This is the entry point of the narrative. The EU economies re-start growing after the financial crisis. There is population and GDP growth, though uneven across the EU.

For the models, assumptions are based on [42] and the EU Reference Scenario 2016 [18].

Policy: '*Stronger decision making/policy parallels within cluster of Member States'*

There is a common general ambition to comply with the Energy Union Strategy, even though with different commitment across Member States, according to the current socio-economic situation, the domestic availability of resources and the geographical location.

For the models, the key numerical assumptions for the near and longer term are based on current decarbonisation targets. They are summarised here:

- The existing binding decarbonisation targets set by the EU 2020 Climate and Energy Package and the 2030 Climate and Energy Framework are taken into account:
  - o By 2020, 20% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
  - o By 2030, 43% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
  - o Effort Sharing Regulation, adopted on May 14th, 2018;
- The indicative 2050 decarbonisation targets, expressed in the EU Roadmap 2050 and in line with the Paris Agreement, are taken into account.
  - o By 2050, 83% decarbonisation target for the ETS sectors in the EU as a whole, compared to 2005 levels;
  - o Decarbonisation targets for 2050 for the non-ETS sectors by groups of countries, according to the current socio-economic situation, the domestic availability of resources and the geographical location, See Table 1 in Appendix A.1.;
- The existing 2020 and 2030 binding targets of renewable share in gross final consumption for the whole EU are kept in consideration and complied with.

Global *setting*: '*Global push to climate change mitigation, driven by some countries/regions*'

There is an uneven push towards climate change mitigation, where certain regions will pursue more ambitious targets than others. In this context, at least two distinct groups are expected to rise outside of the EU:

- One of those having the economic means to decrease their emissions, or threatened the most by climate change, or both.
- The second group includes countries without the economic means to pursue more ambitious environmental targets or seeing the measures against climate change as an unnecessary burden.

Since the focus of the REEEM project is on the European countries, the main numerical assumptions made for this dimension are the GHG emission paths taken by each region outside of the EU. These paths were adopted from Energy Technology Perspectives (ETP) 2017 [43], where a number of global GHG emission pathways based on different ambitions were created. For this work only two were utilised: Reference Technology Scenario (RTS), which considers only current and announced policies and commitments, and the 2 °C Scenario (2DS), which takes into account the necessary emissions' reduction in order to reach the 2 °C target consistent with the Paris agreement.

Table 1, in Appendix A.1, presents the reduction targets of the countries within the Regional Push, meaning that the remaining countries, who also are not part of the EU-28, will continue following the current policies' emission path. Orientation is given by the RTS scenario of the IEA ETP study.

Society: 'Likely *passive society in transition*'

Consumers do not perceive climate change as likely to affect their lives. Therefore, change their consumption habits towards more efficient end-use technologies with high inertia and only in the medium to long term.

Technology: '*Large penetration of centralised renewable energy supply options*'

The decarbonisation targets are met mainly by rollout of large renewable energy supply investments, such as Wind on- and off-shore and Solar PV. Breakthrough in off-shore wind by introduction of floating platforms for wind turbines contributes to the penetration of the technology. Nuclear, biomass and CCS play a role.

The techno-economic characteristics of the technologies are assumed to a large extent according to projections from Ref. [44]. In Table 3, the key bounds assumed for technologies in different sectors are listed.

Table 3

Key technology bounds assumed for the CL pathway.

Health and climate	Health damage costs for selected pollutants are included in the system cost minimization function, as computed in REEEM WP5 (reference); RCP4.5 is assumed as reference for cooling and heating degree-days changes.
Industry	Decarbonisation target imposed to industry-processes + industry-energy in TIMES PanEU, to simulate the increased pressure on large consumers. In 230 750 Mt, in 2050 295 Mt maximum CO_2 emission level is defined.
Residential	
Heat pumps	Share of ambient heat (used by heat pumps) in final energy consumption in residential limited to 8%.
Solar heaters	Solar limited to 5% share of energy consumption in Residential sector, to allow decarbonisation of residential in other ways.
Transportation	No target or limit, nor particular assumptions.
Electricity	
RES Targets	No target on final consumption, as the drive of the scenario is supply.
Off- and on-shore wind	Wind expected to reach 327 GW onshore +50/100 GW offshore by 2030 (REMAP) - 569000 + 170/204000 jobs created. TIMES results for overshoot the target.
Floating off-shore wind	A breakthrough is assumed. Techno-economic assumptions from page 38 of the second REEEM Technology Roadmap [31]
Centralised PV	No target or limit, nor particular assumptions.
Sector coupling	No target or limit, nor particular assumptions.

Environment: 'Low availability of water (drying climate) and scarce resources'

The average temperature, which is positively correlated with evaporation, is projected to rise albeit at a varying level on a European scale. The regional variations include dryer regions of southern Europe becoming relatively warmer. At the same time, Southern Europe is likely to experience less yearly average precipitation resulting in a decreased net availability of water in already dry regions. In addition, although associated with a larger uncertainty, the variability is also projected to change into more extreme events concentrating e.g. rainfall to shorter periods where a larger share is lost through runoff as opposed less intense events supporting the build-up/recharge of water storage in soil and groundwater. Also, periods of droughts are likely to occur more frequently and for longer periods.

The assumptions on the climate are included in the analysis through environmental models and databases: data from the Cordex database [45] for RCP4.5 feeds the Heating and Cooling demand changes analysis and the water availability in TIMES PanEU.

A.4. Detailed assumptions for the Local Solutions

Environment: '*Recognition of the impacts of climate change*'.

This is the entry point for the narrative. Citizens recognise the impacts of climate change, with the media and information campaigns reinforcing this with more comprehensive coverage of events inside and outside the EU.

The real effects of climate change are the same as in the CL pathway. Only their recognition by the society is stronger. Therefore, the assumptions are the same as in the CL pathway: i.e. data from the Cordex [45] database for RCP4.5 feeds the Heating and Cooling demand changes analysis and the water availability.

Society: 'Change *of EU citizens' perception towards climate change and resulting behavioural shifts*'

This change in perception is driven by the factors described under the environmental dimension. It leads households to change their energy investments and energy consumption behaviour, thereby accelerating the transition.

In the models, the change in perception by consumers is represented by pushing the residential and road transportation sectors (not included in the Emission Trading Scheme) to decarbonise more than they would on pure cost optimisation grounds. Detailed assumptions are shared under the technology dimension.

Technology: '*Uptake of low carbon technologies in households and road transport*'

Consumers are more concerned of climate issues and take decisions in order to reduce their carbon footprint. Therefore, low carbon technologies emerge in the residential and transportation sector even if they do not represent the least cost option. Detailed assumptions are shown in Table 4.

Table 4
Key technology bounds assumed for the LS pathway.

Health and Environment	Health damage costs for selected pollutants are included in the system cost minimization function, as computed in Ref. [32] RCP4.5 is assumed as reference for cooling and heating degree-days changes.
Industry	No target or limit, nor particular assumptions
Residential	Ad hoc decarbonisation targets are introduced for the whole sector. In 230 233 Mt, in 2050 60 Mt maximum CO_2 emission level is defined
Heat pumps	No target or limit, nor particular assumptions
Solar heaters	No target or limit, nor particular assumptions
Rooftop PV	Breakthrough in Battery-Integrated Photovoltaic (BIPV) technology. Techno-economic assumptions from page 52 of the second REEEM Technology Roadmap [31]. List of advancements the assumptions correspond to at page 47 of the same document [31]
Transportation	Ad hoc decarbonisation targets in the whole transport sector to favour electrification are introduced. In 230 446 Mt, in 2050 80 Mt maximum CO_2 emission level is defined excluding international transport modes.
Electricity	CCS and expansion of nuclear not allowed.
RES Targets	No target or limit, nor particular assumptions
Off- and on-shore wind	No target or limit, nor particular assumptions
Floating off-shore wind	No target or limit, nor particular assumptions
Centralised PV	No target or limit, nor particular assumptions
Sector coupling	No target or limit, nor particular assumptions.

Policy: '*Pace of local solutions leaves policy making lagging behind in the near to medium term*'

Society moves quicker than realised by decision makers, resulting in a shift in policy emphasis from influencing household decisions in the near to mid-term to those more centralised sectors (power, industry, conversion, agriculture) which may require stronger government intervention. Post 2030, a comprehensive policy package is needed across all sectors to deal with 'lagards' and hard-to-mitigate sectors, including all of those policies already planned. While such package is solid and in place for sectors under the Emission Trading Scheme, it is more fragmented in the non-ETS sectors depending on the higher or lower level of ambition of Member States.

In the modelling, the same policy assumptions regarding ambition as in the CL pathway are made.

Economy: '*Growth at* different *speeds'*

The market offer for technologies for low-carbon decentralised supply follows the demand by consumers. However, the change in demand by consumers is driven by increased awareness rather than financial considerations. No subsidies, nor increased availability of capital drive such change. The behavioural change is expected to impact deeply the structure of investments in low-carbon technologies. This, in turn, is expected to bear an effect on the development of energy supply chains, employment, structure of economy and, ultimately, GDP.

For the models, the initial assumptions are based on [42] and the EU Reference Scenario 2016 [18]. The potential effect of the different structure of energy investments on the economy is not an a-priori assumption, but is derived within by soft-linking the energy model TIMES PanEU and the CGE model NEWAGE.

Global setting: '*Global push to climate change mitigation driven by some regions/countries'*

There is an uneven push towards climate change mitigation, where certain regions will pursue more ambitious targets than others. In this context, at least two distinct groups are expected to rise outside of the EU:

- One of those having the economic means to decrease their emissions, or threatened the most by climate change, or both.
- The second group includes countries without the economic means to pursue more ambitious environmental targets or seeing the measures against climate change as an unnecessary burden.

The main numerical assumptions made for this dimension are the GHG emission paths taken by each region outside of the EU. These paths were adopted from Ref. [43] where a number of global GHG emission pathways based on different ambitions were created. For this work only two were utilised: Reference Technology Scenario (RTS), which considers only current and announced policies and commitments, and the 2 °C Scenario (2DS), which takes into account the necessary emissions' reduction in order to reach the 2 °C target consistent with the Paris agreement.

Table 2 in the Appendix presents the reduction targets of the countries within the Regional Push, meaning that the remaining countries, who also are not part of the EU28, will continue following the current policies' emission path. Orientation is given by the RTS scenario of the IEA ETP study.

A.5. Detailed assumptions for Paris Agreement

Environment: '*General strong recognition of the impacts of climate change*'.

This is the entry point for the narrative. Both Governments and citizens recognise the impacts of climate change, with the media and information campaigns reinforcing this with more comprehensive coverage of events inside and outside the EU.

The real effects of climate change are the same as in the CL pathway, at the beginning. However, the strong recognition and immediate action taken by Governments and societies around the world changes the tendency of climate change and mitigates global warming in the long run. Therefore, RCP2.6 is assumed, to compute the changes in heating and cooling demands in the EU.

Policy: '*The EU takes the lead in fulfilling its obligations under the Paris Agreement*'

The commitment of the EU to lead the way to decarbonisation and fulfil the Paris Agreement translates into a target of 95% GHGs emission reduction by 2050 in the Union, compared to 1990.

Society: '*Change of EU citizens' perception towards climate change and resulting behavioural shifts*'

This change in perception is driven by the factors described under the environmental dimension. It leads households to change their energy investment and using behaviour, thereby accelerating the transition.

In the models, the change in perception by consumers is represented by pushing the residential and road transportation sectors (not included in the Emission Trading Scheme) to decarbonise more than they would on pure cost optimisation grounds. Detailed assumptions are shared under the technology dimension.

Technology: ' *Large penetration of low-carbon energy technologies both in centralised supply and at end-use level*'. Investments in low-carbon technologies are made by consumers, energy carrier suppliers and Governments. Detailed assumptions are given in Table 5.

Table 5
Key technology bounds assumed for the PA pathway.

Health and environment	Introduce damage costs, RCP2.6 [32]
Industry	No target or limit, nor particular assumptions
Residential	No target or limit, nor particular assumptions
Heat pumps	No target or limit, nor particular assumptions
Solar heaters	No target or limit, nor particular assumptions
Rooftop PV	Breakthrough in Battery-Integrated Photovoltaic (BIPV) technology. Techno-economic assumptions from page 52 of the second REEEM Technology Roadmap [31]
Transportation	No target or limit, nor particular assumptions
RES Targets	No target or limit, nor particular assumptions
Off- and on-shore wind	No target or limit, nor particular assumptions
Floating off-shore wind	A breakthrough is assumed. Techno-economic assumptions from page 38 of the second REEEM Technology Roadmap [31].
Ocean energy	No target or limit, nor particular assumptions
Centralised PV	No target or limit, nor particular assumptions
Sector coupling	No target or limit, nor particular assumptions

Economy: ‘Competitiveness *of the EU potentially affected by rapid shift to low-carbon economy’*

The markets observe the sharp change in the climate policy framework initially passively. The energy industry is forced to change deeply and move away to fossil fuel-fired generation. This might affect its competitiveness and the job market until after 2030. In the longer run, some sectors are affected negatively, while others emerge/flourish (unevenly distributed between countries).

For the models, the initial assumptions are based on [42] and the EU Reference Scenario 2016 [18]. The potential effect of the different structure of energy investments on the economy is not an a-priori assumption, but is derived by soft-linking the energy model TIMES PanEU and the CGE model NEWAGE.

Global setting: ‘Global *R&D push to climate change mitigation’*

There is a global push towards climate change mitigation. The emission trajectories for regions outside the EU aligned with 2 Degree Scenario (2DS) of [43].

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3.4 Publication IV

Incorporating uncertainties in the transition towards a sustainable European energy system: a stochastic approach for decarbonization paths focusing on the transport sector

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Incorporating uncertainties towards a sustainable European energy system: A stochastic approach for decarbonization paths focusing on the transport sector

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ABSTRACT

According to the Paris Agreement, the European energy system transition is essential to achieve GHG emission reduction targets set by the EU and limit the growth of global temperatures. Investigating the role of emerging mitigation technologies and their uncertainties together with the different GHG reduction targets is crucial to realize this transition. This study analyzes the uncertainties of electric vehicles' learning paths and biomass availability for biofuels, considering policy uncertainties. Since these technologies are considered possible alternatives to conventional fuels to reduce CO_2 emissions in transport, it is critical to understand their future role and the possible impact of their uncertainties during the European energy system design in case of different climate ambitions. Stochastic modeling is applied to analyze associated uncertainties as an additional approach to a traditional sensitivity analysis. Our results show that decarbonization of car transport is prioritized, and electric cars appear as no-regret options in the sector's design during the energy transition. Therefore, early deployments of EVs are essential to hedge the given uncertainties independent of the hedging period's length. Longer resolution time reduces the deployment of electric vehicles in the recourse strategies compared to having a shorter one due to a delay in the cost reductions. This decline becomes more evident with the stochastic analysis. The policy uncertainty of decarbonization targets has the highest impact on the studied uncertainties on the development of the transport sector. The transport sector can show faster adjustments considering the technology portfolio's shorter lifetime. Thanks to this adjustment, the sector depicts higher decarbonization in the hedging as well as in the recourse strategies.

1. Introduction

1.1. Motivation

The European Union (EU) has strong targets to reduce greenhouse gas (GHG) emissions by 2050 to fulfill the Paris Agreement's goals. A minimum 80% reduction from 1990 levels across all sectors is required by 2050 [1]. In the latest scenario analyses published in Refs. [1,2] by the European Commission, achieving net-zero emissions in 2050 is also discussed. To achieve the aimed reduction targets, all the sectors in the energy system should reduce their emissions as much as economically feasible.

In 2017, transport emissions excluding international aviation and waterborne transport represented close to 22% of the total emissions in the EU, which shows a significant role for emission mitigation in this sector to meet existing and future ambitions in energy and climate policy [1]. In contrast to other sectors, no decline has been experienced since 1990. On the contrary, GHG emissions from transport continue to rise, and in 2017 were 20% higher than in 1990 (excluding international aviation and waterborne). Thus, abating transport emissions remains challenging. These numbers do not seem promising to achieve at least a 60% reduction in this sector relative to the level in 1990 by 2050 to meet the overall decarbonization targets in the energy system [3].

Currently, most transport technologies use liquid fossil fuels. Oil-based fuels represented 93% of the energy consumed in the transport sector in 2016: air transport and waterborne transport rely almost entirely on petroleum products, road transport depended on petroleum products for 95%, but rail transport for only 30% [1]. Road transport has the highest demand across all transport modes and is the biggest emitter with more than 70% of all transport-related GHG emissions. The EU's

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share of renewable energy in transport reached 7% in 2016. Biodiesel appeared as the most widely used form of renewable energy with 11 Mtoe, followed by bioethanol with 2.6 Mtoe. However, biofuel consumption has slightly declined since 2014. Renewable electricity in transport still represented only 1.9 Mtoe in 2016, but its contribution has been significantly increasing recently, with the majority of it consumed in rail transport [1]. Therefore, one of the main elements of the decarbonization strategy in the transport sector is to speed up the deployment of low-emission alternative energy for transport.

According to a recent study [4], transport is again identified as the most challenging sector to decarbonize among all non-ETS sectors. The decomposition analysis carried out in Ref. [4] showed that the electricity share is expected to increase in the sector's final energy consumption. The foreseen additional cost reductions on electric vehicles (EVs) classify the technology as the main mitigation option. Biofuels appeared as the second mitigation option. Advanced biofuels are favorable due to the required engine structure, which is similar to the conventional ones and can offer a compelling route to decarbonization [5].

Biomass is a limited resource and can be utilized as a mitigation option in different parts of the energy system. Besides, it is also necessary to address the limitations and questions concerning existing potential and sustainability conditions. EVs are increasingly cost-competitive due to cost reduction experienced in the battery packs resulting from technological learning [6,7], as shown in the decomposition analysis results [4]. Their share is foreseen to increase even in low reduction scenarios such as the EU Reference Scenario [8]. Different learning curves are already available in the literature to reflect the impact of potentially high deployments of the technology on the cost figures [6,7,9]. Different studies have assessed the impact of uncertainty in learning rates, particularly on the projected investment cost of different technologies such as solar PV, wind, and their outcomes in the energy system analysis [10–12]. EVs might offer a potentially easier route to decarbonize the sector than biofuels as there are no concerns about the limited potential or sustainability of the energy source. However, there are also discussions on the limitation of the required materials in the battery packs, e.g., lithium-ion. Besides, the effects of having different reduction targets for the GHG emissions in the EU energy system on the development of the transport sector are discussed in Ref. [13]. The results demonstrated that a higher reduction target brings higher electrification. However, the amount of biofuels does not always increase with a higher reduction target due to the biomass allocation in the other sectors.

Relatively few studies are available in the literature that examines the uncertainty around those technology pathways, such as the learning rate of EVs and the availability of sustainable biomass to be utilized in the transport sector considering different reduction targets in the EU energy system. The biomass allocation concerns the entire energy system since the biomass potential is determined for the overall use, not only specific to a single sector. Additionally, the provision of electricity and other energy carriers for transport need to compete with other sectors such as heat or industry during the decarbonization of the energy system. Therefore, an energy system analysis covering the entire energy system, which considers the sectoral cause-effect relationships between transport and other sectors, is required to define the transport sector's decarbonization paths with the relevant uncertainties. This analysis is necessary to forecast the transport sector's role more realistically through the energy transition in the EU.

1.2. Selection of the approach to address the uncertainty

In order to better analyze the aspects mentioned above considering the relevant uncertainties in the transport sector, the development of a new methodological approach is necessary. Different approaches are developed in the literature to address the uncertainties in the energy system analysis with different energy system models [14–17]. According to the systematic review in Ref. [17], there are mainly four approaches applied to energy system models additional to sensitivity analysis: Monte Carlo analysis, stochastic programming, robust optimization, and modeling to generate alternatives. [18] differentiates the uncertainties studied in the energy systems as parametric and structural. While parametric uncertainties refer to the values for the input assumptions given to the model due to lack of knowledge, structural uncertainties are defined as the ones in the model equations. Based on these definitions, the uncertainties we want to study in this paper are classified as parametric uncertainties. As stated in Ref. [17], parametric uncertainties cannot be addressed with the modeling to generate alternatives approach. Between the other methods, a reliable probability distribution is required for the uncertain parameters for the Monte Carlo analysis. Additionally, high numbers of scenarios are necessary, increasing the computational time for the analysis. This is especially an issue when dealing with already complex and computationally intensive models, such as Pan-European energy system models. As it is not possible to overcome the burden of computational time, Monte Carlo analysis is also not applicable for this study. The alternative approach of robust optimization does not require probability distributions. However, it also does not provide a unified hedging strategy [17]. Here, hedging strategy refers to the near-term (stochastic) modeling results up to the point of uncertainty resolution, i.e., it describes the optimal strategy to minimize possible adverse impacts from uncertain future developments. In contrast, results after resolving the uncertainty are referred to as recourse strategies. To derive a single hedging and possible recourse strategies for a limited, small number of considered uncertainties, stochastic programming can be introduced in energy system models. Since the near-term hedging strategy is also in our interest, we opted for the stochastic programming approach to analyze uncertainties in the transport sector in our study together with the deterministic sensitivity analysis since the deterministic sensitivity analysis is identified as a standard method to deal with the uncertainties [19]. As we study only a limited number of uncertainties, the impacts can be examined with these approaches by optimizing computational time. Additionally, stochastic programming enables us to quantify and analyze the related costs of the uncertainties and compare them with the deterministic results as a result of sensitivity analysis. Therefore, this study applies stochastic programming, which takes advantage of the positive aspects of the various approaches such as near-term hedging strategy and optimized computational time.

1.3. Literature review

Sensitivity analysis is a standard method in energy system analysis to support policy decisions related to uncertainties [19]. In our study, stochastic programming is chosen as an additional approach to standard sensitivity analysis to investigate the uncertainties' impact considering the positive aspects, as discussed in Section 1.2. Therefore, studies, which applied the same approach in the literature, are reviewed.

Stochastic programming is introduced as a method to address the technology cost uncertainties in the energy system model by applying the MESSAGE model in Ref. [20]. The aim is to include the uncertainties in the decision structure in the model. They suggest that applying the stochastic approach improves the model behavior and provides more robust results, although they might be costlier to the system in some instances. Stochastic programming is also applied in the electricity model, OseMOSYS, to evaluate the impact of the policy uncertainties on electricity market capacity planning [21]. Three policy scenarios - carbon cap, carbon tax, and renewable portfolio standard - are analyzed with different policy levels (no policy, weak, moderate, strong, and very strong), each associated with different probabilities. The comparison with deterministic results shows that the optimal hedging strategy delays decarbonization under the carbon tax scenario. However, in the carbon cap and the renewable portfolio standard scenario, the hedging strategy results in more action in the early periods than the wait-and-see approach. Additionally, the cost of uncertainty appears to be highest under the renewable policy standard scenario and lowest in the carbon tax scenario.

In [22], an integrated investment model is developed, including both the gas and electricity markets. They applied stochastic programming to analyze the impact of the gas demand uncertainty in other sectors, affecting decision-making processes for the investment in electricity generation capacities. According to their findings, this uncertainty brings a re-allocation of investments in gas-fired power plants. In another study, the uncertainty of fossil fuel prices and biomass import availability in the UK is assessed for the optimal near-term decisions by employing a two-stage stochastic energy system model [23]. The fossil fuel price uncertainty causes higher system cost than the uncertainty of biomass import.

Multi-stage stochastic optimization of a simple energy system model is developed in Ref. [24]. The model is applied to investigate the uncertainties of oil and natural gas prices on energy system development. Their results indicate that the uncertainties on oil prices might significantly impact the system cost than natural gas prices uncertainties. They also conclude that the energy system is robust by considering the uncertainties since only minor impacts are observed on the system's technology deployment. Since the hedging period is limited to 5 years in the analysis, the hedging period's insights are also restricted. Stochastic scenario tree and Monte Carlo simulation together are applied to address the power generation expansion planning problem in the Indonesian power generation system in Ref. [25]. Uncertainties around fuel (coal, natural gas, and diesel) prices, the cost of the selected technologies, and electricity demand growth during the time horizon are explored. The unpredictability of the fuel prices is analyzed with Monte Carlo simulation. Electricity demand uncertainty and the uncertainty around the cost of renewable energy technologies are addressed by achieving the government's CO_2 emission targets through the stochastic scenario tree. CO_2 emission reduction targets are implemented in the study, considering renewable energy penetration targets, annual construction limits, and carbon pricing policy. Their modeling work shows that assigning a statistical distribution for given variables enables the continuous consideration of uncertainties in the electricity system design.

TIAM-World model is further developed with stochastic programming in Ref. [26] and applied to analyze the hedging strategies considering the contrasted technology outlooks. Hedging strategy determined the robust technologies by taking into account different probabilities in stochastic programming. Their findings show that natural gas is a robust technology regarding the uncertainties between different technology options. Lower emissions and the low capital cost of the technology make the technology appealing, especially in China. Higher natural gas deployment is also seen in the hedging strategy than in the other deterministic scenarios. However, nuclear power and carbon capture storages (CCS) are identified as less robust technologies. Their deployment depends on different factors such as climate targets or the probabilities of the technology outlooks. In Ref. [27], the intermittent characteristics of wind power are modeled in a TIMES model built for the Danish heat and electricity sector by applying stochastic modeling to assess the uncertainty with the wind generation profile of the country. In the stochastic model, the total energy system cost is lower than deterministic runs due to the reductions in wind investments and electricity exports. In Ref. [28], different climate targets and CO_2 storage availability uncertainties are explored with the TIAM-ECN, a global energy system model. Stochastic modeling is employed, and the results are compared to deterministic runs similar to the approach in Ref. [23]. They developed a two-stage stochastic model and concluded that strong climate targets dominate the solution. Early movements are required to achieve the targets, such as the availability of CO_2 storage.

1.4. Research aim and the structure

Based on the current literature review, uncertainties have not yet been analyzed with a Pan-European model to identify their impacts on the EU energy system's decarbonization, focusing on a single sector development such as transport. Therefore, the impacts of the learning uncertainty of battery packs in EVs, and the uncertainty of biomass availability on the transport sector decarbonization considering the policy uncertainty are analyzed in the EU energy transition in the scope of this study. For this, the TIMES PanEU energy system model is first applied to carry out the traditional sensitivity analysis and further developed by applying stochastic programming.

The uncertainties mentioned above are studied in the two-stage stochastic model by applying 80% and 90% GHG reduction targets in 2050 across the energy system based on the 1990 level. Stochastic results are compared with the equivalent deterministic runs. Moreover, the different hedging period's influence is explored by altering the uncertainty resolution time in an additional analysis. Since the reduction target appears as another significant uncertainty on the transport sector's development, further analysis is carried out by combining the reduction target uncertainty in the energy system with biomass uncertainty in the transport sector. The expected value of perfect information (EVPI) is calculated as an indicator to assess the potential influence of uncertainty on overall costs. The EVPI depicts the difference in system costs between the stochastic results and the hypothetical case if it is known in advance, which of the scenarios will become a reality.

The article is structured as follows: In section 2, the model TIMES PanEU, stochastic modeling, and the selection of the uncertainties in the study are described. The results from the deterministic analysis are explained in detail in Section 3. In Section 4, insights from the stochastic programming analysis are elaborated and discussed. Finally, in Section 5, key conclusions are stated, and further research areas are identified.

2. Methodology and scenario construction

In Section 2.1., the energy system model employed in the study, TIMES PanEU, is introduced. In Section 2.2., the modeling approach applied in the study, stochastic programming, and selection of the uncertain parameters with the scenario assumptions are described.

2.1. TIMES PanEU model

TIMES PanEU is employed as an energy system optimization model to investigate the development of the transport sector considering the relevant uncertainties discussed in Section 1.1. TIMES PanEU is selected since it has the detailed representation of the technologies available today and for the future and can apply stochastic modeling for the uncertainty assessment in the transport sector [29]. Additionally, it has already been widely applied in the existing literature to deliver policy-relevant insights considering the interactions between different energy system sectors [4,13,30].

TIMES PanEU is based on the modeling environment GAMS and the TIMES model generator [31]. TIMES creates bottom-up energy system models with linear programming. It has been maintained and developed within the Energy Technology System Analyses Program by the International Energy Agency [31]. The data management system (VEDA-TIMES) creates an energy system model [32,33]. The input data, model's structure, and all the scenario-related information are given to the model. Then, these data are converted to mathematical equations.

The model's objective function minimizes the total discounted system cost in a given timeframe, meeting exogenously given service demands with a perfect foresight principle [34]. TIMES PanEU covers the EU 27 countries as well as Norway, Switzerland, and the United Kingdom. Each country represents a single region in the model.

The modeling horizon spans from 2010 to 2050, split into 5 year-time steps. 5 year-time steps results are calculated as the average of 5 years, 2 years before, and 2 years after each time step. For example, if the results are analyzed for 2020, these results should be examined as the average values for the period between 2018 and 2022. A year is divided into 12 time-slices, 4-seasonal, and 3-day level (day, peak, and night). The basic structure of the model is called a reference energy system (RES). The RES includes all relevant energy, material, and emission flow from the primary production to meet the demand for energy services for each region defined in the model [35,36]. Thus, the entire energy system, from the supply of resources to the service demand, is covered in the RES of the model.

Primary energy sources are modeled according to country potentials and the trade possibilities from the neighboring countries. The World Energy Outlook prices [37] and average country mining costs are taken as a reference to determine the cost figures for sources such as crude oil, natural gas, or coal. Various bioenergy carriers such as rapeseeds, sugar crops, starch crops, woody crops, and grassy crops are included by considering the country potentials, land use, and costs with a step-wise approach [38]. No constraints are considered for biomass trade between the EU countries. Land availability for biomass cultivation is given in the model based on [38].

The transport sector is disaggregated according to different transportation modes. Car transport demand is further disaggregated as short and long distances. Dimethyl ether, diesel, gasoline, gas, LPG technologies are available as conventional ones. Together with hybrid technologies with gasoline, diesel, gas, and ethanol options, electric cars are also implemented. Ethanol, biodiesel, and hydrogen cars are offered as technology options to fulfill the given car transport demand. Bus transport demand is further disaggregated as intercity and urban. Similar to car transport, gasoline, biodiesel, ethanol, gas, and hydrogen technologies are available for this transport mode. The electric vehicle (EV) option is available for the urban mode together with the diesel hybrid option. Due to the availability of the urban mode, EVs are modeled for this transport model. However, they are not defined as technology options for the intercity demand. Other transport demands are defined as motorcycle, trains (passenger and freight), light and heavy-duty transport, air traffic (international and domestic), and waterborne (international and domestic). Passenger transport is modeled in the unit of Passenger-km (Pkm), whereas freight transport is modeled in Ton-km (Tkm). The technology options are similar in terms of the variation between car transport and freight transport. Electric vehicles option as a hybrid technology with gasoline, diesel, gas, and ethanol are available additional to the conventional fuel technologies in light and heavy-duty transport. Different vehicle technologies based on the different energy carriers are modeled for each demand category mentioned above.

Aviation and waterborne sectors are modeled as generic processes in TIMES PanEU, which means there is no defined investment cost and the cost optimization of the system only depends on the cost of the fuel and the CO_2 emission coefficient. For the decarbonization of these transport modes, mitigation options are modeled as well. In Ref. [39], the milestones in terms of technological improvement are defined for the mitigation options. These milestones are considered in TIMES PanEU as annual constraints to the availability of the technologies. In aviation, biokerosene for domestic and international flights is modeled as an option starting from 2015. Biodiesel is given as an option for domestic flights starting from 2025 and international flights from 2035 on. A maximum 10% share of the domestic flights demand can be met through electricity in 2035. A maximum of 10% of the domestic flight demand can be provided by hydrogen in 2035. These levels increase to 15% of electricity and 20% hydrogen by 2050 for the same transportation mode. For international flights, a maximum of 5% of the demand is set for the share of electricity and hydrogen in 2050. In waterborne transport, LNG, biodiesel, and biokerosene are defined as options starting from 2025, in line with the milestones in Ref. [39]. LNG prices are taken from the World Energy Outlook [37]. Electricity and hydrogen are given as options starting from 2035.

In the electricity sector, the electricity supply at different voltage levels is modeled through different technologies. The large central power plants feed to high voltage grid, while decentralized generation such as PV systems feeds to medium and low voltage grids. New technologies such as electricity storages, hydrogen technologies, natural gas, and coal CCS technologies are modeled as investment options during the time horizon.

The industrial sector is divided into energy-intensive and non-energy-intensive industries. The energy-intensive industries cover iron and steel, aluminum, copper, ammonia, chlorine, cement, lime, flat glass, and paper. In contrast, the non-energy-intensive industries include other non-ferrous metals, other chemicals, other non-metallic minerals, food and tobacco, and other industries. Industrial auto producers are also modeled as part of the energy system [40].

The energy service demands are disaggregated according to different purposes in the household, commercial, and agriculture segments. Various technologies, aggregated according to technology type and energy carrier, are implemented to meet energy service demands. The underlying assumptions of the existing demand figures in TIMES PanEU are consistent with the socio-demographic assumptions of the EU Reference Scenario [8].

All major greenhouse gas emissions (CO_2, CH_4, N_2O) are also included in the model. In addition, emissions from the agricultural sector are modeled, along with certain mitigation technologies to cover the scope of the Paris Agreement. These emissions are caused by fertilizers and livestock (manure management, enteric fermentation). Emissions from pollutants (SO_2, NO_x, CO, NMVOC, $PM_{2.5}$, PM_{10}) are part of the model as well [4].

2.2. Modeling uncertainty

2.2.1. Stochastic programming with TIMES

Stochastic programming is a method to make optimal decisions under uncertainty. As explained in Section 1.2. in addition to a traditional sensitivity analysis, it is chosen as a further approach in our study. In a deterministic model, uncertainties are often assessed through sensitivity analysis. Stochastic bottom-up energy system models optimize the discounted system cost of future State of the Worlds (SOW) according to the weighted average of given probabilities [23]. Instead of single deterministic values for all parameters, different distributions for specific parameters can be defined through stochastic programming, and the model incorporates the uncertainty coming from these different distributions.

A stochastic model is defined based on a scenario tree that identifies the random variables for a single parameter. The probability for each SOW is defined exogenously. This probability determines the likelihood of uncertainty to occur. According to the given probability and specific assumptions defined by the assigned uncertainty and on an SOW, the model calculates the optimized hedging strategy and recourse strategies, taking into account the expected cost of the uncertainty in the system.

Mathematically, the stochastic model relaxes the assumption of perfect foresight by splitting the time horizon into a single near-term hedging strategy and multiple recourse periods. In contrast, a deterministic model calculates a single solution. The objective function of the stochastic model is defined as follows:

Minimize:

$$\sum_{w\,\in\,W\,(t)} . \sum_{t\in T} C\,(t,w)\,X(t,w).P\,(t,w)$$

Where:

w : *the SOW*

t : *the time period*

$W(t)$: *the set of SOWs for time period t*

T : *a set of all time periods*

$C\,(t,w)$: *the row vector in time period t under SOW w*

$X(t,w)$: *the column vector of decision variables in period t, under scenario w*, $C\,(t,w)$

$P\,(t,w)$: *theprobabilityofthescenariowinperiodt.and*;

$$\sum_{w\,\in\,W(t)} P\,(t,w) = 1$$

According to the optimization function and optimized hedging strategy, TIMES calculates the set of results according to the total numbers of the SOWs in the last stage based on the given probability and one objective function which considers the cost of uncertainty for the random variables [29]. Model results before the uncertainty is resolved are called the hedge. The set of results for the period after the uncertainty is resolved (recourse strategies) depend on the number of the SOWs defined in the last stage.

The expected value of perfect information (EVPI) can be calculated to show the difference in cost between the stochastic modeling and deterministic scenario analyses in which uncertainty is entirely removed. The equivalent deterministic scenarios should be computed after calculating the stochastic run [23] to calculate EVPI. In the deterministic runs, the model makes the decisions under perfect information for the specific SOW parameters. The equation to calculate the EVPI is given as below:

$$EVPI = COSThedge - \sum_{i=1}^{k} Pi^{*}COSTpfi$$

Where:

$COSThedge$: *the cost of the stochastic model*

$COSTpfi$: *the cost of each deterministic model equivalent SOW*.

Our study applies the TIMES PanEU model, explained in Section 2.1, with stochastic programming to investigate the impacts of the uncertainties and their criticality in the transport sector during the EU energy transition. As a first step, the relevant parameters for the analysis are determined. As explained in Section 1.2., we focus on three uncertainties for the transport sector's future development.

2.2.2. *Uncertainty on a GHG reduction target*

To achieve the commitments, according to the Paris Agreement [41], the EU must realize an energy transition to reduce GHG emissions by 2050. To execute this transition, different reduction targets determined based on the 1990 emissions are under discussion. Therefore, the latest analysis in Ref. [1] discusses the reduction target scenarios between 80% and net-zero emissions in 2050. Although a minimum 80% reduction target is intended, the ambitions have recently been raised to higher than 80% with the European Green Deal [2]. Therefore, the effect of having different reduction targets on the development of the transport sector needs to be considered [13].

2.2.3. *Uncertainty on battery learning rates*

As elaborated in Section 2.1., EVs are already implemented as technology options in the existing model structure of TIMES PanEU. The cost assumptions for the vehicles are based on [42]. Studies in the existing literature have found different learnings and cost projections for the large-scale lithium-ion batteries and battery packs in electric vehicles [6,7]. To project the future cost of such a technology, learning curves are a widely applied methodology. The cost of a technology is defined as a cumulative production function, and according to the principle of learning curves, costs decrease with cumulative installed capacity. The learning rate then indicates the fractional cost reduction of a technology when the cumulative capacity is doubled globally [43]. Since TIMES PanEU covers only the European regions, the cost assumptions based on global learning are given exogenously. In Ref. [7], five different product price curves are developed according to the S curve approach for the deployment and learning rates of the battery packs in EVs based on the learning curve principle. Historical product prices and cumulative installed capacities based on peer-reviewed literature are used to derive the learning rates in Ref. [7]. The learning rates calculated are in the 16% ± 4 interval. The middle learning scenarios did not result in any significant differences compared to existing assumptions in the deterministic TIMES PanEU version so, they were not applied as a part of the analysis.

The highest and lowest reduction curves of battery packs presented in this paper are incorporated in our study to determine the EVs' cost paths. As different cost curves are available in Ref. [7], to be consistent for the source of the information and reliable comparability for high and low learning scenarios, we only apply for those numbers from this study. These cost figures for battery packs are incorporated into the vehicles' existing cost figures in TIMES PanEU, based on [42] to reflect the technology's cost reduction. Different learning rates result in the 13% cost difference for the battery electric vehicles starting from 2030. This difference is relatively lower for the plug-in hybrids, which is around 2% due to the share of the batteries' cost. The uncertainty range is similar to the electric trucks and buses, around 12%, but this interval is moderately small for hybrid technologies, 2%. Detailed cost assumptions used for battery costs and the electric vehicles in high learning and low learning scenarios as part of this study, are given in Appendix A 1 and Appendix A 2.

2.2.4. *Biomass availability in the transport sector*

Biomass and the fuels sourced from biomass are anticipated as mitigation options in many parts of the energy system [13,44]. With the development of new technologies such as biomass CCS, concerns are also raised concerning the availability of the source for non-CCS applications [45]. According to previous TIMES PanEU results based on several scenarios with different reduction targets [13], the share of biomass in 2020 in the final energy consumption of transport is calculated around 10%. In the low biomass availability scenario in this paper, the maximum share of biofuels is kept at 2020 levels as calculated in the scenarios mentioned in Ref. [13], which represent a lower bound in development regarding the given renewable targets for 2020 [46]. Based on previous model results considering the total final energy consumption of transport in 2050 [13], we defined that the absolute amount of biofuels in EU28 should not exceed 1500 PJ as the maximum potential in 2050 for the low biomass availability in the transport sector. The analysis in Ref. [13] and the biomass bounds calculation are given in Appendix B 1. We did not define any bound for biomass usage in the transport sector in high biomass potential availability. Therefore, the uncertainty range in terms of biomass availability is enormous as we only determined the bound for the low biomass potential in the transport sector. However, according to regions explained in Section 2.1, biomass availability is still considered a total potential for the entire energy system in both cases.

3. Parameter variations – deterministic analysis

As described in the previous section, the impact of uncertainties around the cost of EVs, biomass availability in the transport sector, and the GHG reduction target on the development of the transport sector are investigated. First, we carry out a sensitivity analysis with 8 variants considering the parameters defined in Section 2.2. For this analysis, we structure the scenarios as given in Table 1. Cost assumptions for the EVs as well as biofuel amounts, given as input assumptions to the model, can be found in Appendix A and Appendix B. For the 80% reduction target in 2050, we assume the following milestone targets: 50% in 2030, 60% in 2040. As explained in Section 2.2.2, more ambitious reduction targets are already under discussion [1]. Therefore, additional analysis with a

Table 1
Uncertainty model runs - Deterministic analysis.

2050 GHG Reduction Target	Learning in EVs	Biomass Potential	Deterministic Analysis
80% according to the level in 1990	High Learning (HL)	High Biomass (HB)	80%_HL-HB
	High Learning (HL)	Low Biomass (LB)	80%_HL-LB
	Low Learning (LL)	High Biomass (HB)	80%_LL-HB
	Low Learning (LL)	Low Biomass (LB)	80%_LL-LB
90% according to the level in 1990	High Learning (HL)	High Biomass (HB)	90%_HL-HB
	High Learning (HL)	Low Biomass (LB)	90%_HL-LB
	Low Learning (LL)	High Biomass (HB)	90%_LL-HB
	Low Learning (LL)	Low Biomass (LB)	90%_LL-LB

higher reduction target of 90% is performed by applying the same scenario variations given in Table 1. This reduction target is implemented with the following milestones: 50% in 2030 and 70% in 2040.

For the sensitivity analysis, the variations in Table 1 are first conducted as single deterministic scenarios. Fig. 1 shows the final energy consumption in the transport sector for the results according to the variations defined in Table 1 with the 80% reduction target. As the biomass availability limitation is considered only for the domestic transport modes, international aviation and waterborne transport are not part of Fig. 1.

Due to the decarbonization target, the energy carriers' share in the transport sector changes drastically in 2050 compared to 2015. The shares of conventional sources such as diesel and gasoline are over 90% in 2015. This value goes down to less than half of the total consumption in 2050 in all the runs (Fig. 1), along with the decarbonization target as well as efficiency improvements with the technologies in the sector. The lowest share of the conventional sources in 2050 is seen when there are high learning and high biomass availability; HL – HB results. On the other hand, when there are limited biomass and higher cost figures for EVs, such as Low Learning – Low Biomass variation (LL – LB results), the share of conventional fuels is still over 40%. The share of electricity starts increasing in 2030 in all the runs along with the decarbonization targets and reducing the cost of the EVs. EVs mostly dominate the vehicle market for car transport in 2050. Similar growth in biofuel cars is also seen.

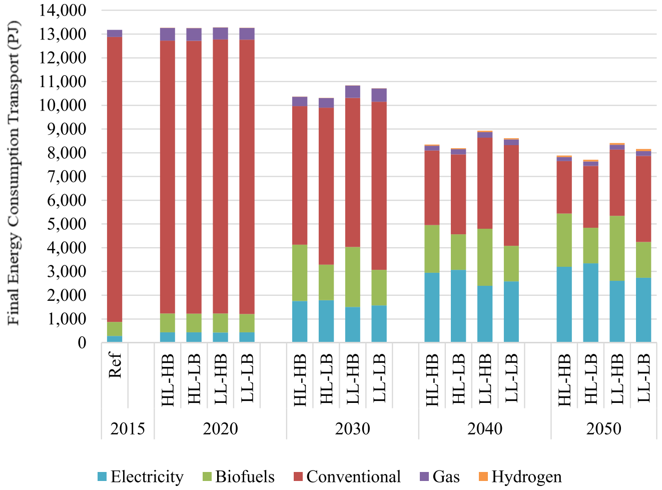


Fig. 1. Final energy consumption in transport (without international aviation and waterborne) for 80% reduction target – Deterministic sensitivity analysis.

In the Low Learning scenarios; Low Learning – High Biomass (LL - HB) and Low Learning – Low Biomass (LL – LB), the share of electricity is less than 35% in 2050. Although the conventional carriers' shares look different in the high learning scenarios; High Learning – High Biomass (HL-HB) and High Learning - Low Biomass (HL-LB), due to the different biomass availability, this has only slightly impacted the total final energy consumption numbers. The differences between Low Learning (LL) and High Learning (HL) scenarios' total final energy consumption mainly come from different learning. The EVs can reduce the total final energy consumption with a higher deployment. For the same reason, when low learning is assumed; in Low Learning – High Biomass (LL - HB) and Low Learning – Low Biomass (LB –LB) scenarios, total final energy consumption in the sector also increases. Overall, the total final energy consumption numbers in the 80% reduction target are mostly affected by the technology learning uncertainty with the EVs due to efficiency differences between the EVs and conventional vehicles. However, even with the low learning results, EVs will still have a particular share (Fig. 1).

In all the scenarios with an 80% reduction target, biofuels' utilization in the car transport segment is higher than other transport modes due to the higher contribution of this mode in the total final energy consumption (Fig. 2). If there is high learning, EVs will also have a higher share in the car transport. If the EV option is limited by low learning, car transport still has a priority in decarbonization because of its higher demand and share in GHG emissions. Therefore, more biofuels are allocated to this transport mode in all Low Learning (LL) scenarios. In the case of an 80% reduction target and limited biomass potential (LB SOWs), biofuels are only consumed in aviation, car, and freight transport. Decarbonization of the waterborne is not prioritized when there is biofuel limitation in the transport sector, independent of the assumed learning. Instead of decarbonizing the waterborne, the model again prefers to allocate most of the potential to car transport. The model continues to utilize the petroleum products in waterborne in the limited biomass availability scenarios.

In the 90% reduction target results, the conventional sources' shares are around 20% in 2050 in all the scenario variations given in Table 1. Due to the higher decarbonization target in these runs, the shares go down to 22% even in the Low Learning – Low Biomass (LL-LB) scenarios. Concerning total final energy consumption numbers, differences between the different scenarios are similar to the 80% reduction target results. However, these differences are less significant in 2040. As the model tries to achieve higher decarbonization targets in the early stage, the share of electricity consumption increases significantly in most of the scenarios already in 2040, while these numbers are achieved only in 2050 in case of an 80% reduction target results (Fig. 3). With the higher deployment of EVs, final energy consumption also experiences reductions already in 2040. Due to the higher reduction target, higher electricity consumption in the transport sector is seen even in the Low Learning (LL) scenarios (Fig. 3). It shows that in a higher reduction

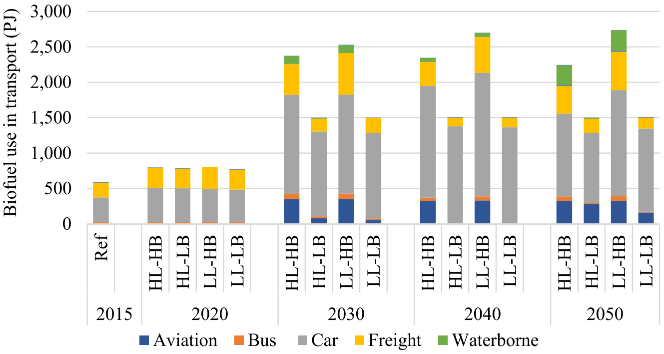


Fig. 2. Biofuel use in transport (without international aviation and waterborne) for 80% reduction target – Deterministic sensitivity analysis.

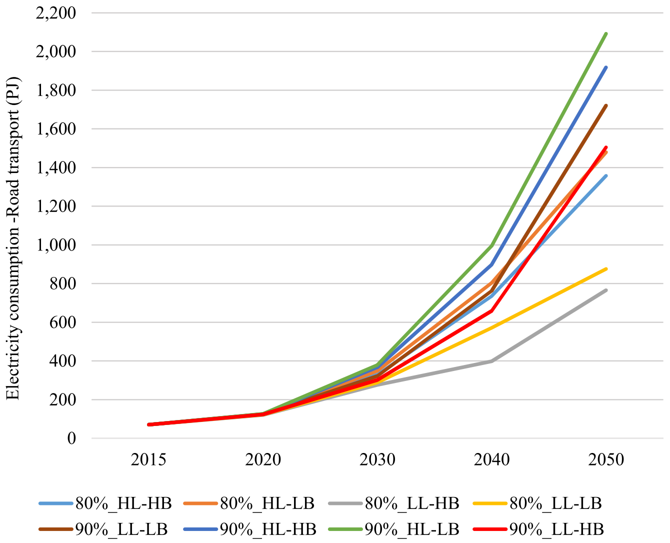


Fig. 3. Electricity consumption in road transport – Deterministic sensitivity analysis.

target scenario (90% reduction target), the impact of the learning uncertainty of EVs becomes less relevant with a higher decarbonization target in such a sensitivity analysis.

A particular usage of biofuels characterizes all transport modes in 2050 in all the scenario variations with a 90% reduction target. Unlike the 80% reduction target results, the biofuel utilization in car transport is restricted in the case of limited availability of biomass and low learning; Low Learning – Low Biomass (LL-LB), to a similar level as in the case of high learning; High Learning – Low Biomass (HL-LB). Despite the higher decarbonization target in the 90% reduction scenario, biomass utilization in transport is lower in 2050 in High Biomass scenarios (Appendix C 1).

As biomass can be employed as a mitigation option in different sectors and has limited potential in the energy system, in the 90% scenario, the priority is given to other sectors such as industry. With the advantage of using TIMES PanEU, which covers the entire energy system for such an analysis, the allocation of biomass according to different sectors with different reduction targets, is also identified. In the 90% reduction target scenario, biomass utilization increases, especially in the industry, since the mitigation options are somewhat limited in this sector starting from 2040. With the 90% reduction target, a slightly increasing biomass utilization is also seen in electricity. Higher electricity usage independent of the assumed learning in road transport compensates for the lower biomass usage in transport (Fig. 3).

As a result of deterministic sensitivity analysis considering the biomass availability, EV development, and policy uncertainty, it is concluded that in the 80% reduction target, the different scenario variations show a higher difference respective to the uncertainties. High and low biofuel usage differs 1237 PJ in the 80% reduction results, whereas this number goes down to 801 PJ in the 90% reduction results. Similar differences are also seen with the total electricity consumption in road transport. 603 PJ difference in the 80% reduction target runs reduces to 414 PJ in the 90% reduction target runs. The detailed numbers are given in Appendix C 2.

4. Stochastic analysis

As described in Section 1.2., stochastic programming is chosen as the method to investigate the impact of uncertainties in addition to the sensitivity analysis (Section 3). In Section 2.2, stochastic programming and considered uncertainties together with the minimum and maximum values to be applied in the High and Low scenarios are explained as well. For this purpose, we first examine these uncertainties with the help of a stochastic tree with the 80% and 90% reduction target scenarios across EU27 and UK in the entire energy system similar to the analysis in Section 3. The stochastic scenario tree structure for the analyses and the findings are explained in Section 4.1. To study the effect of having a longer hedging period on the system design, in a further sensitivity analysis, we change the stochastic tree structure by extending the hedging period in Section 4.2. In section 4.3., we combine the biomass uncertainty with the reduction target uncertainty and build a new stochastic tree. Objective functions of deterministic and stochastic analyses are discussed together with the calculated expected value of perfect information from each analysis in Section 4.4. Finally, in Section 4.5. the analysis is further elaborated with the integrated discussion of the findings.

4.1. *Stochastic analysis – shorter hedging (until 2020)*

Since the aim is to study the impact of learning uncertainty for battery packs in EVs and the uncertainty of biomass availability by going beyond sensitivity analysis to gain insights, these two factors determine the State of the Worlds (SOWs) in the stochastic tree according to the methodology in Section 2.2. As the current version of the stochastic programming implementation in TIMES is based on directly solving the equivalent deterministic problem as explained in Section 2.1., we apply the scenario variations in Table 1 to build the stochastic scenario tree. Since the EV costs and biomass potential are also expected to vary after 2025 according to the assumptions explained in Section 2.2., the second stage of the stochastic tree is assumed to be commenced after 2025 according to the same assumptions in Section 3. The definition of absolute numbers is explained in Section 2.2. Based on this, a two-stage stochastic tree with four SOWs is developed and implemented with TIMES PanEU. The highest and lowest learning scenarios in Ref. [7] are applied in our study for battery packs in EVs, as clarified in Section 2.2.3. Low biomass and high biomass availability scenarios are further integrated into the scenario tree. Biomass availability and the learning scenarios are combined as schemed in Fig. 5. Equal probabilities are given to each SOW due to a lack of information regarding the likelihood of possible development. This approach has already been applied in different studies [23, 47]. This means that each of the four SOWs has a 25% chance of occurring.

The stochastic tree (Fig. 5) is applied for the 80% and 90% reduction target scenarios with the same milestones in the sensitivity analysis in Section 3 and structured in Table 1. According to the stochastic scenario tree (Fig. 5), which is built considering the currently expected resolution date of the given uncertainties, the hedging period covers only 2020. As explained in Section 2.1., the results given for this year refer to the average values between 2018 and 2022. Some non-significant variations are observed for the final energy consumption mix in the transport sector, compared to the deterministic analysis carried out in Section 3. In the hedging strategy, electricity consumption is higher than in all the deterministic runs. This difference in the final energy consumption mix reduces the share of conventional sources. Although the overall contribution from gas to the final energy consumption is not high in the transport sector, seen in Fig. 1, the hedging period optimizes its total use. In the High Learning (HL) deterministic runs, its use is overestimated. However, in Low Learning (LL) deterministic results, the application seems relatively low compared to the hedging strategy. In the hedging period, biomass utilization is also optimized. High Learning – Low Biomass (HL-LB) SOW deterministic results give almost identical results in terms of biomass utilization, but in High Biomass (HB) SOWs, the contribution might be slightly overemphasized whereas in Low Learning – Low Biomass (LL-LB) SOW is underestimated. High Learning – Low Biomass (HL-LB) SOW shows the closest allocation to hedging strategy considering given limitation with biomass use and foreseen higher cost reductions (Appendix C 3).

As the differences between hedging and deterministic runs are pretty limited, this could be interpreted as the uncertainty's impact on decision-making in this period is relatively low. The results confirm that the impact of the considered uncertainties on short-term decisions in the decarbonization paths is limited, similar to the outcomes in Ref. [24]. These limited variances between stochastic and deterministic results are also persisted in the periods after the uncertainty is resolved (Fig. 6). We followed the approach given in similar studies [21,23] by comparing the recourse strategy's stochastic results with the equivalent deterministic results to present our findings. Although the differences are more visible between the energy carrier shares in the deterministic runs compared to stochastic runs, the decarbonization targets mainly determine the path for further developing the transport sector. In 2050, the differences become less evident since the decarbonization target also turns out to be more ambitious over time.

In the stochastic results, higher deployment of EVs is observed in the early periods in all the SOW results compared to deterministic results. As a result, the electricity use is increased across all the SOWs between 8% and 25%. In return, the share of conventional sources decreases 6%–12%, and the gas use is also decreased substantially, although the overall contribution to final energy consumption from this source is not high (Fig. 1). The results show that early deployments are necessary considering the uncertainty with the cost of the technology, especially right after the uncertainty is resolved. These early deployments also help to reduce the total energy consumption in the sector thanks to the higher efficiency of EVs, especially in the Low Learning (LL) SOWs compared to deterministic results. Additionally, a reduced share of conventional sources in the early periods speeds up the decarbonization of the sector.

Low Learning – High Biomass (LL-HB) SOWs result in the highest variance between deterministic and stochastic results with an 80% reduction target. Due to the impact of the considered uncertainty, higher deployment of EVs is seen in the stochastic results, and biomass utilization is also optimized considering the biomass boundaries coming from the Low Biomass (LB) SOWs. The deterministic analysis has shown that in the case of Low Learning (LL), available biomass potential is mainly utilized in car transport (Fig. 2), and waterborne is only decarbonized when there is a higher potential for biomass. This trend is also mainly followed in the stochastic results. Only in the case of Low Learning - High Biomass (LL-HB), with the help of the early deployments, EVs could achieve higher deployments in the stochastic results; in return, biomass use can be optimized since the required burden for the car transport is mainly taken by the EVs in this SOW. In deterministic results, higher biofuels are also utilized in 2040 and 2050 in Low Learning – High Biomass (LL-HB) SOW, which is replaced with EVs in the stochastic results.

As a result of the stochastic programming, the differences between the high and low SOWs become smaller in 2050, at the end of the recourse period (Appendix C 4). Higher deployment of EVs in the Low Learning (LL) SOWs and slightly lower deployment of EV in the High Learning (HL) SOWs reduces the differences between the results to 438 PJ, whereas this is calculated as 603 PJ in deterministic 80% reduction target results. Biofuel differences also reduce from 1237 PJ (deterministic analysis) to 992 PJ (stochastic results). Similar to the findings with deterministic runs, the higher reduction target reduces the difference even further. The amount of electricity used in EVs between the high and low SOWs differs by only 310 PJ, and the amount of biofuel by 609 PJ in the 90% reduction target results. Thus, even with a stochastic analysis, the reduction target seems to be the leading driver of the system transformation.

4.2. *Stochastic analysis – longer hedging (until 2035)*

In Section 4.1, the analysis shows a limit to how far investments can be changed in the short hedging period. Therefore, we conduct a sensitivity analysis to investigate the impacts of having a longer hedging period for the considered uncertainties. The related model runs in this section are listed in Table 2. We perform this analysis with an 80% reduction target since the effect of the uncertainties becomes less visible with higher reduction targets, as discussed in Sections 3 and 4.1. As the aim is to have a longer hedging period, we shift the beginning of the 2nd stage to 2040 instead of 2025. Therefore, the stochastic scenario tree in Fig. 5 is restructured, as shown in Fig. 7. Biomass bound in transport is kept constant at 1500 PJ in all the SOWs until 2040. In High Biomass (HB) SOWs, this bound is relaxed afterward, but the overall biomass potential in the energy system is still taken into account. The learning regarding EVs is also kept constant until 2040, after which a strong reduction in the battery packs is assumed in High Learning (HL) SOWs. The EV assumptions for this scenario tree are also given detailed in Appendix A 2 and Appendix A 3. Similar to the analysis conducted in Section 4.1., equivalent deterministic runs are also carried out, and insights are discussed as the relative differences between stochastic and deterministic results. Equal probability for each SOW, 25% probability, is defined similarly to the analysis in Section 4.1.

Table 2
Uncertainty model runs – Longer hedging period.

Uncertainties	Deterministic	Stochastic
High Learning - High Biomass	D_HL-HB	S_HL-HB
Low Learning - Low Biomass	D_HL-LB	S_HL-LB
High Learning - High Biomass	D_LL-HB	S_LL-HB
Low Learning - Low Biomass	D_LL-LB	S_LL-LB

Until the uncertainties are resolved in 2040, especially in 2020 and 2025, in the hedging period, higher deployment of EVs in road transport is seen, to be specific mainly in car and freight transport, compared to deterministic runs. In 2030 and 2035, before the uncertainty is resolved in the last periods, the hedging strategy follows a trend similar to the High Learning (HL) deterministic results. For better visualization, we select two SOWs with the highest and lowest electricity consumption for both stochastic and deterministic results and present the results in Fig. 8a. The electricity consumption for all other SOWs is presented in Appendix C 6. High Learning (HL) SOWs result in relatively similar paths when comparing stochastic and deterministic runs after resolving the system's uncertainties. Although the differences are not significant, more prominent variations are seen with the Low Learning (LL) SOWs. According to deterministic results (D_LL-HB), the electricity consumption varies between 765 and 1478 PJ. This range narrows down to 889 & 1380 PJ in 2050 in the stochastic results (S_LL-HB in Fig. 8b).

The total electricity consumption in road transport, representing EV deployment, is more affected by having a more extended hedging period. As a result of stochastic analysis with a longer hedging period, a transition to EVs might be accelerated in the mid-term (2030 and 2035). The hedging strategy provides 7,5% higher consumption than the Low Learning-High Biomass (LL-HB) SOW in 2035. The difference between the hedging strategy and the equivalent stochastic result compared to a shorter hedging period is even 10% higher. Having the perspective of early cost reductions in the High Learning case increases the potential deployment in the Low Learning cases in the recourse period, after the uncertainties are resolved (Fig. 8b). However, as seen in Fig. 8a, postponing the cost reductions with the EVs until 2040 reduces the deployment in both Low Learning SOWs and the High Learning SOWs. This drop in deployment becomes even more visible with the stochastic analysis. According to stochastic analysis, electricity consumption with a shorter hedging period varies between 889 and 1380 PJ in 2050. With a longer hedging period, this range declines to 840 to 1103 PJ. The detailed numbers are also presented in Appendix C 4 and Appendix C 5.

As a result of having earlier deployment with the EVs in the hedging strategy, a longer hedging period brings alterations in this period to utilize the biomass potential in different transport modes, specifically in aviation and car transport. Starting from 2030, aviation increases its biofuel usage between 15% and 50% compared to deterministic results. Similar findings are also observed with freight transport. Biomass is accordingly shifted from car transport, where biomass utilization sees a slight loss due to the hedging strategy, as a result of earlier deployments of EVs. After the uncertainty is resolved in 2040 and 2050, the transport modes folow a parallel pattern similar to the short hedging period (Section 4.1.) in both deterministic and stochastic results in biomass utilization (Fig. 4). In High Biomass (HB) SOWs, starting from 2040, waterborne also starts decarbonizing by employing biofuels in the energy mix. Still, in Low Biomass (LB) SOWs, car transport takes the leading share, like the findings in Section 3 and 4.1. High Learning – High Biomass (HL-HB) SOWs results do not show significant differences between deterministic and stochastic in this period.

4.3. Combining biomass uncertainty with a reduction target uncertainty

This section brings together the policy uncertainty considering the entire energy system and biomass uncertainty in the transport sector. As discussed in Sections 3 and 4.1, the uncertainty, especially with EVs, becomes irrelevant in the system design with the higher reduction target. On the other hand, biomass utilization might bring different insights from other sectors in the energy system, especially in higher reduction target scenarios. It can be used as a mitigation option in the other sectors, as discussed in Section 3 and already identified in similar studies [13]. Therefore, we combine these two uncertainties, policy uncertainty with having different decarbonization targets and biomass availability, to study the transport sector's design by considering the feedback from and to the other sectors in the energy system. According to currently discussed targets concerning the Green Deal [2], the emission reduction path aims to achieve a 50% GHG reduction in 2030 based on 1990 levels. Based on this assumption, the uncertainty associated with the GHG reduction target will resolve in 2035. In light of this information, we structure the scenario tree as given in Fig. 9 by initiating the 2nd stage in 2035. Until the 2nd stage, biomass bound again is kept constant as 1500 PJ across all the SOWs in the transport sector. After 2030, the reduction target milestones in 2040 are implemented as described in Section 3 with an 80% Reduction Target SOW and 90% Reduction Target SOW. Equal probabilities are assigned for each SOW. For the EVs, high learning assumptions are incorporated across the SOWs, as given in Appendix A. The related model runs in this section are listed in Table 3.

The stochastic mode's hedging strategy results do not show any significant differences in 2020 (period 2018–2022), as seen in Fig. 10, compared to the deterministic results. In terms of the system development, 5 years appear too short to hedge for different reduction targets, as analyzed in Section 4.1. Since the reduction targets are identical in both deterministic and stochastic modes until 2035, the total level of emissions is mostly identical in this period as well. On the other hand, specific hedging strategies are developed in 2030. In the hedging strategy, emissions from the electricity sector appear to be higher relative to deterministic results in this period (Fig. 10). The electricity sector does not seem to act as fast as the other sectors, such as transport and industry, to respond to the uncertainty. This slower adaptation of technologies in the electricity sector shows its impacts in the recourse period as well. Thanks to the possibilities to adapt faster, transport decarbonizes more in the stochastic runs, taking the burden from the electricity sector. This higher contribution to decarbonization in the recourse period in the stochastic results continues despite the bound for the biofuel usage in the transport sector in the Low Biomass (LB) SOWs. Therefore, biomass uncertainty becomes less critical on CO_2 emissions in this sector, especially with the increasing GHG reduction target after the uncertainty is resolved. The biomass utilization in different transport modes in both deterministic and stochastic results shows similar trends as the results discussed in Fig. 3. Higher electricity consumption is seen in Low Biomass (LB) SOWs compared to High Biomass (HB) SOWs with both reduction targets as the other available mitigation option in this sector is limited. Electricity consumption is higher in all the stochastic results compared to respective deterministic results to further reduce CO_2 emissions (see Fig. 11).

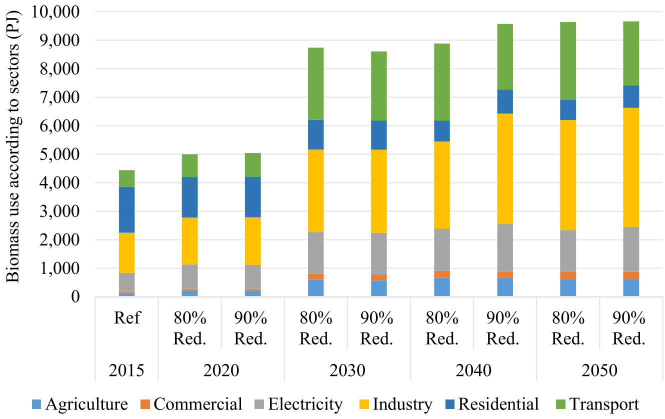


Fig. 4. Biomass use according to sectors – Deterministic sensitivity analysis for Low Learning-High Biomass (LL-HB) Scenarios.

In the industry sector, early actions are taken to decarbonize the sector in the hedging period. Since the mitigation options are somewhat limited in the industry, the different biomass allocation across the sectors results in a difference between deterministic and stochastic modes. Higher biomass utilization is observed as a mitigation option in the stochastic mode compared to all the deterministic runs. The residential sector also follows the same path as the industry sector in the hedging period. Earlier decarbonization seems a possible strategy to hedge the different reduction targets. The deployment of district heating technology helps with these early reactions. Although the electricity sector postpones the decarbonization in the stochastic mode, more biomass utilization is observed in this sector relative to deterministic runs (Fig. 10). This difference in biomass utilization in the electricity sector is mainly employed in CHPs to provide district heating consumed in the residential sector. Incorporating the reduction target uncertainty into the analysis increases biomass utilization in the early periods (hedging strategy). Small differences also appear in the recourse period after the uncertainties are resolved. The relevant figure is given in Appendix C 7.

As seen in Fig. 10, policy uncertainty has an impact on the transport sector's development, considering the relationships with the other sectors. In the hedging strategy, to deal with the policy uncertainty, the transport sector needs to make early moves, especially regarding the lower GHG reduction targets. Since the biomass limitation becomes less relevant concerning the overall system in the short term, EVs' role in the hedging period comes to the focus again. Increased early deployment of EVs fosters early decarbonization in the transport sector. The hedging strategy results in between 11% and 16% higher electricity consumption in road transport relative to the lower reduction target deployments, 80% SOWs. The higher deployments in the stochastic results continue in the recourse period as well. Since the transport sector reduces more emissions in both high and low target SOWs in the recourse period compared to deterministic results, the EV deployment also shows higher numbers in the stochastic results. The higher deployments are also visible between the higher target deterministic and stochastic results (Fig. 11 a and b), with transport continuing to take the burden from the electricity sector, as shown in Appendix C 8.

4.4. Expected value of perfect information

We calculate the expected value of perfect information, explained in Section 2.2.1., for the analyses carried out in Sections 4.1, 4.2, and 4.3 to quantify the reduction in system costs if it is known in advance, which of the scenarios will become a reality [22].

The lowest total system cost belongs to the High Learning – Low Biomass (HL-LB) SOW between the deterministic runs due to the expected cost reductions in EVs according to the analyses in Section 4.1 and 4.2. The lowest system cost in the analysis in Section 4.3. belongs to

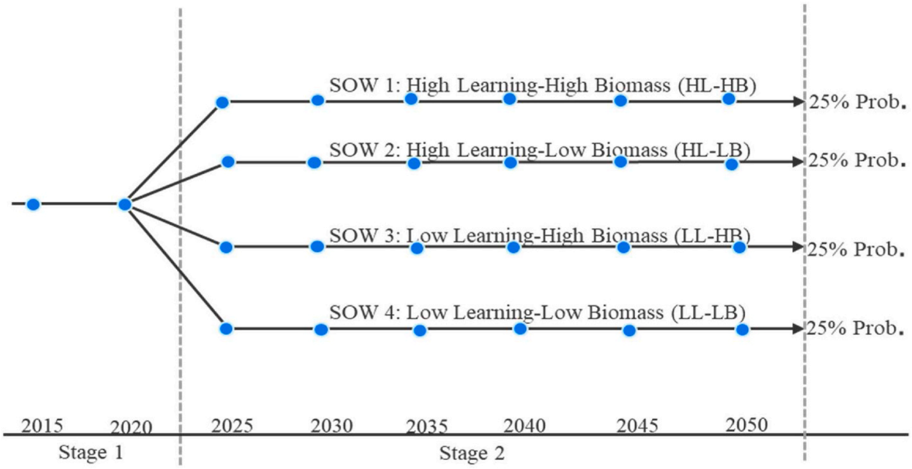


Fig. 5. Stochastic scenario tree – 80% & 90% reduction target.

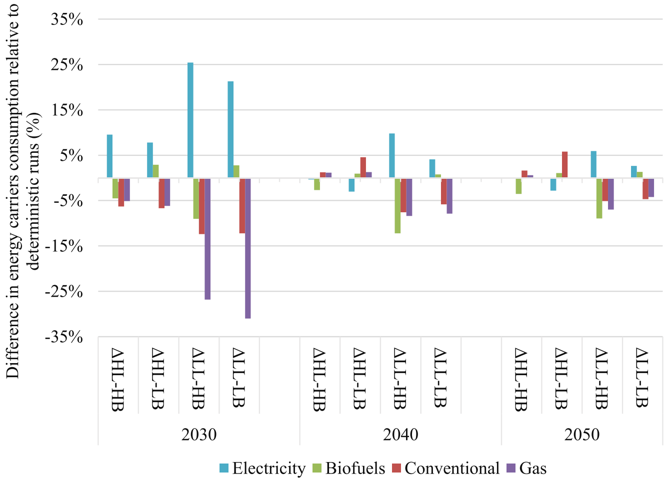


Fig. 6. Difference in energy carriers' consumption relative to deterministic runs (%) – Recourse strategy for the transport sector in 80% reduction target.

the 80% Reduction Target – High Biomass SOW. Differences in terms of the total system cost in all the analyses are nearly invisible between High Learning – High Biomass (HL-HB) and High Learning – Low Biomass (HL-LB) deterministic results due to the EVs' cost. Since EVs are deployed across all the analyses, their deployment is identified as independent from their learning. Therefore, the total system cost is computed as the highest in Low Learning deterministic results, which is also confirmed here. The difference between the High Learning and Low Learning results is lower with the longer hedging period (Table 4).

Since substantial reductions on the EVs' cost are assumed after 2040 in the longer hedging period, the model has limited time to reflect the cost gain also in the High Learning results. These results are displayed in Appendix C 9. A longer hedging period increases the expected value of perfect information. It also has a higher impact than having a higher reduction target on the expected value of perfect information. The impact of postponing the cost reduction in EVs is also confirmed again with the EVPI. However, the highest expected value of perfect information is calculated in the analysis with reduction target and biomass uncertainties together in the system. The reduction target uncertainty concerns the entire energy system. Therefore, this information becomes also more valuable to structure the energy system concerning uncertainty. A higher reduction target also brings higher total system cost since more mitigation options need to be deployed in other parts of the energy system.

4.5. Discussion

Until the uncertainties are resolved in the system, the model has

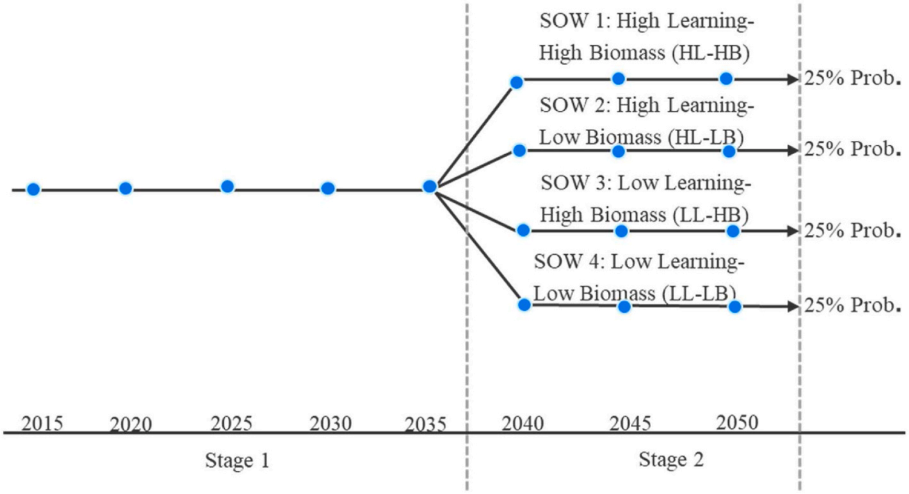


Fig. 7. Stochastic tree – a variation of hedging period with 80% reduction target.

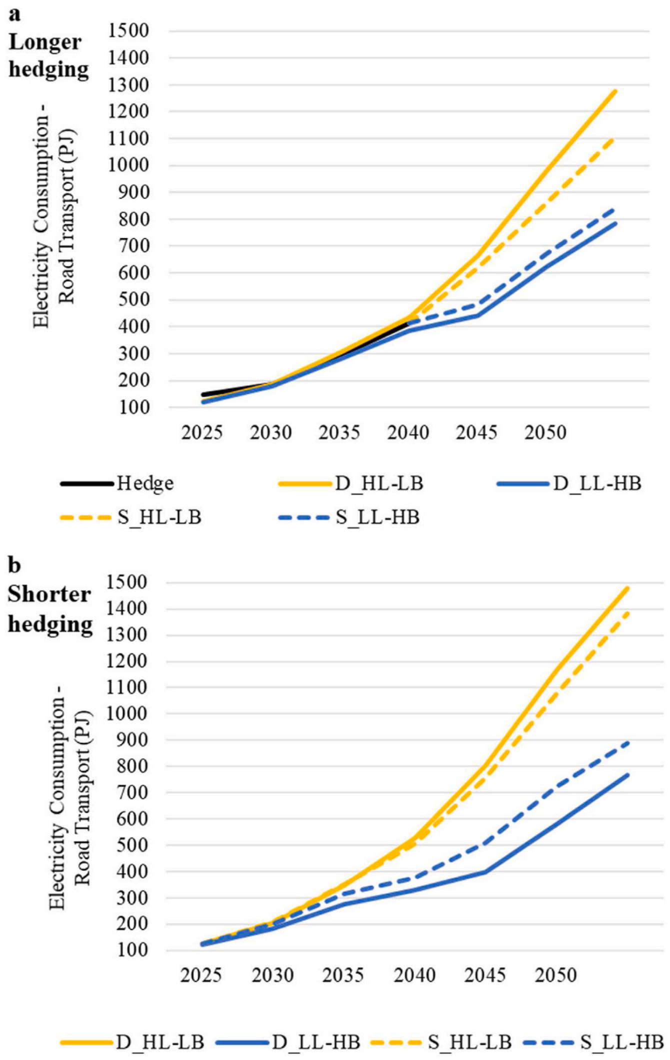


Fig. 8. (a and b) Electricity usage road transport – Longer (a) vs. Shorter (b) hedging period.

Table 3
Uncertainty model runs – Combining biomass uncertainty with a reduction target uncertainty.

Uncertainties	Deterministic	Stochastic
80% Reduction - High Biomass	D_80%-HB	S_80%-HB
80% Reduction - Low Biomass	D_80%-LB	S_80%-LB
90% Reduction - High Biomass	D_90%-HB	S_90%-HB
90% Reduction - Low Biomass	D_90%-LB	S_90%-LB

Table 4
Expected value of perfect information.

Name of the Analysis	Expected value of perfect information	% Relative to the stochastic total system cost
80% Reduction	370,978	0.767%
90% Reduction	375,082	0.770%
Longer Hedging	567,542	1.145%
Red. Target & Biomass Unc.	709,181	1.428%

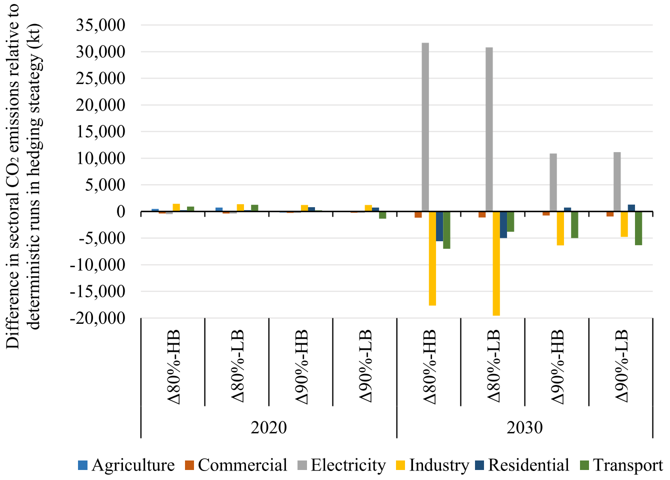


Fig. 10. Difference in sectoral CO_2 emissions relative to deterministic runs (kt) - Hedging strategy.

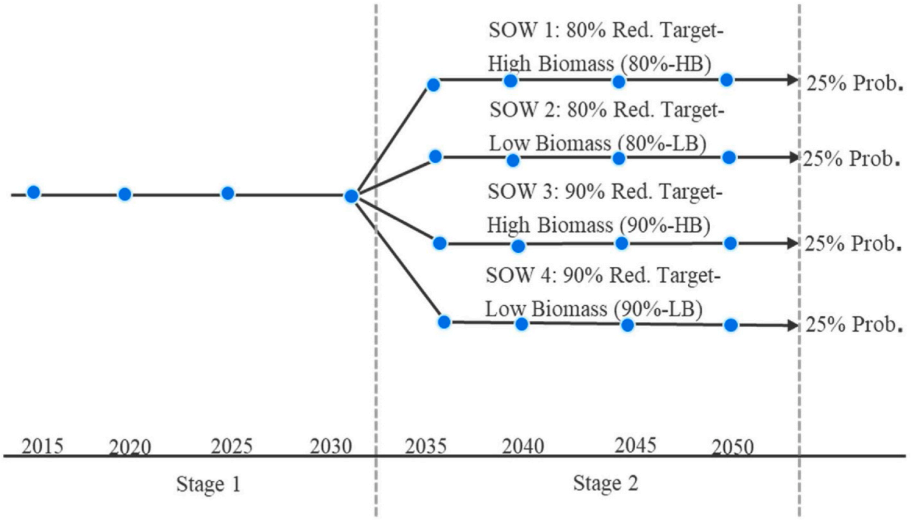


Fig. 9. Stochastic scenario tree – combining reduction target and biomass uncertainties.

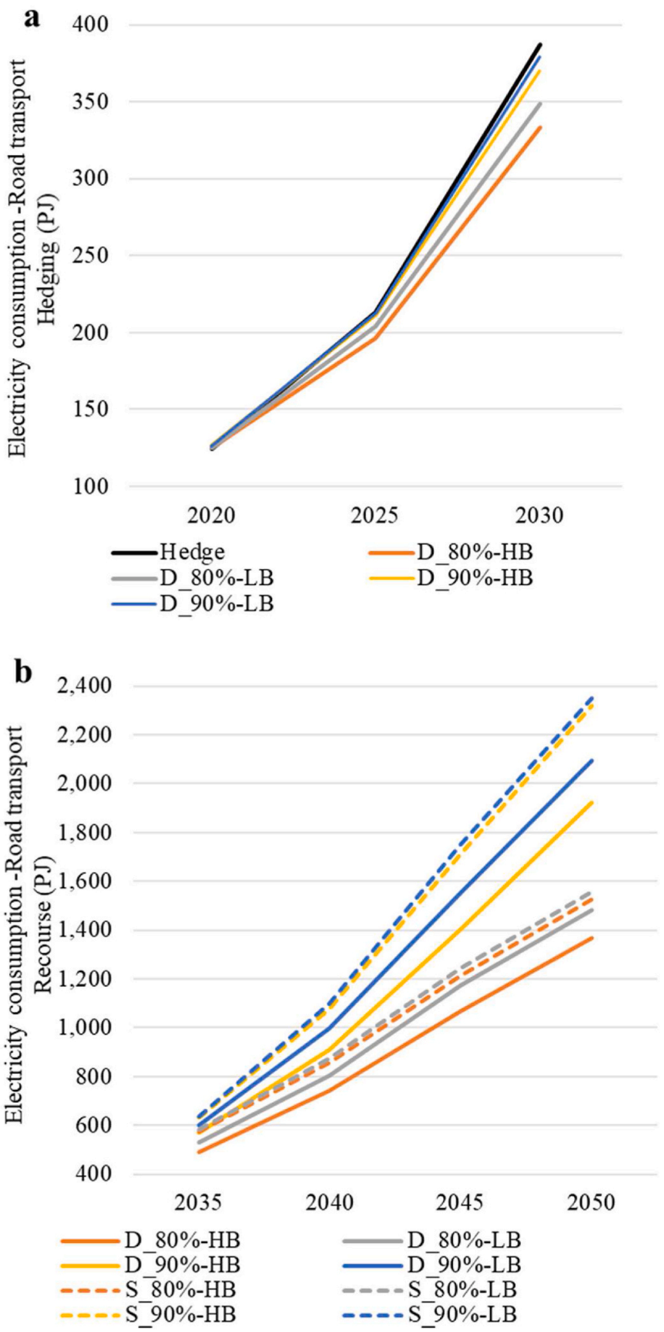


Fig. 11. (a and b) Electricity consumption road transport – Hedging (a) and Recourse (b) period with policy uncertainty.

provided one single set of results for the stochastic version to determine a hedging strategy considering the uncertainties. In both decarbonization scenarios with a shorter hedging period, only 2020, the difference between the proposed hedging strategy and the deterministic runs is not observed to be significant. For the same period, deterministic runs also give very similar results. We only observed a slightly higher deployment of EVs and lower consumption of petroleum products in return. This shows that the hedging strategy is only minimally affected by the uncertainties with a shorter hedging period, which agrees with the findings in Ref. [25]. Considering that there are also near-term decarbonization targets to be met, the small variance between the hedging strategy and all the deterministic results may also indicate that there is only a single path to follow in this period, independent of possible future developments. In the midterm, higher deployments of EVs are also seen in the stochastic results compared to deterministic results. Therefore, to achieve a specific reduction target in the energy system, EVs will be no-regret options, independent of their learning rates. Stochastic results also emphasize the importance of early actions with EV deployment to contend with the given uncertainties.

A two-stage stochastic model with 5-year hedging period is also applied with the higher, 90% reduction target scenario. In the hedging period, with the considered uncertainties, a slightly higher use of EVs is seen. Our results have also shown that a higher reduction target brings a less flexible system in terms of deploying mitigation technologies. When the system gets closer to net-zero emissions, not many feasible choices are left for the system considering the assumed techno-economic parameters of existing options. Parameters such as cost and resource uncertainty become less critical during the design of the system. This can be further supported by the differences between the deterministic and stochastic results. Due to the limited impact of the hedging period and since the "big" targets/drivers only come into the picture later, the considered uncertainties do not limit any recourse strategy option with a shorter hedging period. Therefore, both deterministic and stochastic versions give similar results.

Biofuel uncertainty is mostly critical for waterborne transport, especially in the lower reduction target cases. In case of limited potential, especially with the lower reduction target in the system, car transport will have precedence over the other transport demands. With its high demand, car transport is always prioritized to be decarbonized. Learning uncertainty has a higher impact on the total final energy consumption results in the 80% scenario. As the model tries to optimize the cost, other options are still considered first, if EV costs are not low enough. The impact of uncertainty will be most visible in the last periods of the time horizon due to the learning curve principle. As the cost goes down with the deployment of the technology over time, cost differences between Low Learning (LL) and High Learning (HL) SOWs become more prominent in the later periods. However, EVs reach a particular market share in 2050 in all scenario variations, making them a no-regret option.

The hedging strategy usually provides a single near-term strategy to follow to minimize adverse impacts of future, uncertain developments. To study the effects of a longer hedging period, we altered stage 2 from 2025 to 2040 and applied the 80% reduction target. In this structure, EV cost curves and biomass bounds follow the same path until 2040 with Low Learning (LL) and Low Biomass (LB) SOW assumptions. After 2040, substantial cost reductions are anticipated in the High Learning (HL) SOWs, and in High Biomass (HB) SOWs, the biofuel bound in the transport sector is relaxed. Similar to the analysis with a shorter hedging period, higher deployment of EVs in car and freight transport is seen, especially compared to the Low Learning (LL) deterministic results in the hedging strategy. The results show that if the cost reductions are delayed with the EVs, the deployment potential can shrink for this technology. The stochastic analysis confirmed that a wait-and-see approach might be costlier and reduce the technology's market share even more than anticipated. In the hedging strategy, more biofuels are allocated to aviation and freight and less to car transport, which benefits from a higher EV deployment in the hedging period instead. Therefore, early deployments of EVs will be inevitable if the learning is postponed and car transport appears as the determinative demand. In addition, a longer hedging period brings computational advantages by optimizing the computational time of stochastic programming.

Two different reduction targets have been studied with the biomass and learning uncertainties in the transport sector. Decarbonization paths appear as influential factors: higher reduction targets reduce the system's flexibility. Therefore, we have also analyzed policy uncertainty regarding the reduction targets in the energy system combined with the biomass uncertainty in the transport sector. As seen especially with the higher reduction target in the energy system, the utilization of biomass in the transport sector is affected by a potential sector-specific bound, its utilization in other sectors and EVs as no-regret options. Therefore, we have examined the biomass and the policy uncertainties for the transport sector's future development. Policy uncertainty delays the electricity sector's decarbonization but accelerates deployment of the mitigation options in industry, residential, and transport. Since the lifetime of the technologies is longer in the electricity sector than in other sectors, this sector cannot adopt the policy uncertainties as fast as other sectors. To compensate the inflexibility in the electricity sector, the transport sector might need to take early actions for decarbonization. In the case of a reduction target uncertainty, the shorter lifetime of the technologies can provide more flexibility to the sector. Therefore, mitigation technologies such as EVs, especially compared to the 80% Reduction Target SOWs, will help deal with such uncertainty.

The cost of uncertainty, EVPI matrix, in both 80% and 90% scenarios is computed as 0.77% of total system costs. In a cost-driven optimization, all of these influence the total system costs. Our results also show that a longer hedging period increases the cost of uncertainty, even with the lower reduction target due to the longer time to be hedged. However, the GHG reduction target uncertainty brings the highest cost into the system since it concerns the entire energy system development, not only a single sector.

5. Conclusion & Outlook

This study has contributed to the existing literature by analyzing the impact of uncertainties in the transport sector during the transition to a low carbon energy system in the EU. Uncertainties surrounding biomass availability and the learning rates of battery packs have been analyzed together with reduction target uncertainty with the traditional approach, sensitivity analysis, and stochastic programming in the energy system model, TIMES PanEU. First, 80% and 90% reduction targets from the 1990 emission level have been applied in 2050, considering biomass and EV learning uncertainties in the transport sector. In total, eight different scenario variations have been conducted as sensitivity analyses. Stochastic programming has been applied for the same scenario structure with 2 stages of the stochastic tree resulting in 4 different State of the Worlds (SOWs) for each reduction target by taking a step further from the traditional sensitivity analysis approach, with the resolution time in 2025. We have explored the impacts of these uncertainties on the transport sector's development with 80% and 90% reduction targets. The resolution time of the uncertainty has been altered to 2040. The influence of a longer hedging period in the next phase of our study has also been explored. Following that, biomass uncertainty in the transport sector has been combined with the reduction target uncertainty in the energy system to explore its future development and impact on the energy system. In the end, we have compared the calculated EVPIs to evaluate which information brings a higher cost to the system.

Thanks to stochastic programming, the given uncertainties have been integrated into the energy system analysis to develop hedging strategies to define the short to mid-term actions and recourse strategies with a two-stage stochastic tree without increasing the computational time heavily. Determining the number of the State of the Worlds and the number of stages is identified as a crucial step since a high number of SOWs could easily increase the computational time, which might not be worth the effort. On the other hand, the defined SOWs should cover the uncertainty range, and the number of stages shall be aligned with the foreseen timeline considering the analyzed uncertainties. Therefore, in this study, we have focused on two main SOWs for each given uncertainty considering their likelihood and the uncertainty range. We combined these SOWs by taking into account the foreseen timelines for their resolution time based on the existing literature. Uncertainty range has also been defined considering the minimum and maximum expected values for biomass and EV uncertainties. This approach can also be applied in different parts of the energy system in view of cross-sectoral dynamics to develop hedging and recourse strategies for the relevant uncertainties.

Based on our analysis, in the transport sector development, car transport is the first to be decarbonized due to the highest contribution to the sector's final energy consumption. Therefore, EVs are identified as no-regret options independent of their learning during the decarbonization of the system. Our results also prove that early deployment of EVs is inevitable, independent of the length of the hedging period to hedge the cost reduction uncertainty and policy uncertainty. However, late cost reductions on EVs might slow down the deployment of the technology and bring additional costs to the system. Our study has not considered all the required investments in the supply sector, such as building up infrastructure or production capacities for the EVs, which require long-term planning. Our findings suggest that policymakers should accelerate the associated investments to meet the system's requirements in the long term, including the infrastructure. Since they are no-regret options, they can also bring cost advantages if their deployment happens faster. Furthermore, a high share of EVs can also help the transport sector reduce the overall energy consumption in the sector by helping to achieve the energy efficiency targets and support other sectors to have more flexibility in case of policy changes in the mid-term.

While we have considered learning uncertainties of battery packs as one critical part of EVs, we have not considered the emissions born during these batteries' manufacturing. This may mean that their decarbonization potential is overestimated in this study. Therefore, as further research, we suggest that the life cycle emissions should be considered to define the decarbonization paths. Furthermore, EVs' decarbonization potential may also be overestimated since we have not integrated demand shifts between transport modes. As the current traffic system is concentrated on individual modes, changing the transport from individual to the public might create significant differences in GHG emissions, impacting the priority to decarbonize car transport. Similarly, the current and potential development of transport infrastructure, such as charging networks, has not been considered in the scope of the study. Nevertheless, infrastructure is critical for adopting new technology, and related uncertainties should be included in further analyses.

Our results also showed that the transport sector shows higher potential for early decarbonization considering the reduction uncertainties in the system with a hedging strategy for biomass utilization, highlighting the importance of stochastic analysis additional to the early deployment of EVs. Considering biomass availability, we have only limited the biomass potential in the transport sector at the EU level in our study and left the rest of the energy system quite flexible for allocating in which countries this resource is used. We have determined this limit based on previous studies according to different scenarios. We also suggest, as further research, that this biomass potential should be defined at the country level, considering the country's potentials and the utilization in other sectors during the decarbonization of the energy system. Additionally, international transportation modes have not been included in the scope of this study. We expect that their involvement might change the impacts of the uncertainties in the system. It is clear that biomass uncertainty directly influences the other sectors since it can be utilized in different parts of the energy system as a mitigation option. Therefore, broader engagement and system view is required in the energy system analysis.

We have not carried out a detailed analysis to calculate the probabilities of different SOWs studied in this study to assess the impact of having different probabilities. However, we performed a sensitivity analysis with a simpler scenario tree only with biomass uncertainty shown in Appendix D. We have not observed any significant results between different stochastic results in the hedging strategy. Therefore, we have not presented the findings in the Results Section. A higher probability for a particular SOW can impact the results in favor of this SOW in the stochastic results. However, in our study, this has not been the main focus. Further research focusing on the different probabilities with detailed data analysis concerning the new uncertainties in the energy system can bring stochastic modeling insights.

Sample credit author statement

Pinar Korkmaz: Conceptualization, Methodology, Writing – original draft preparation, Formal analysis, Visualization, Investigation, Dorothea Schmidt: Reviewing and Editing, Ulrich Fahl: Supervision, Writing-Reviewing and Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX A

Appendix A 1
High Learning Cost Assumptions

High Learning-Cost Assumptions	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Cost Batterypack	$/kWh	350	270	180	62.5	50	37.5	31.5	31.5
Conversion Rate	€/$	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Cost Batterypack	€/kWh	304	235	157	54	43	33	27	27
Electric Cars	€/vehicle	49,589	48,758	46,337	41,255	40,787	40,250	40,012	40,101
Electric Cars with Gasoline range extender	€/vehicle	47,093	45,854	44,512	42,886	42,756	42,627	42,565	42,565
Electric Cars with Diesel range extender	€/vehicle	49,743	48,461	47,075	45,405	45,275	45,146	45,084	45,084
Electric Cars with Natural gas range extender	€/vehicle	55,563	54,075	52,483	50,607	50,451	50,294	50,205	50,177
Electric Cars with Ethanol range extender	€/vehicle	53,304	51,883	50,358	48,548	48,399	48,250	48,167	48,147
Electric Truck with Gasoline range extender	€/vehicle	48,744	46,872	44,600	41,462	41,184	40,890	40,754	40,774
Electric Truck with Diesel range extender	€/vehicle	50,488	48,588	46,286	43,119	42,842	42,548	42,412	42,431
Electric Truck with Natural gas range extender	€/vehicle	53,891	51,777	49,261	45,880	45,574	45,252	45,087	45,078
Electric Truck with Ethanol range extender	€/vehicle	50,488	48,588	46,286	43,119	42,842	42,548	42,412	42,431
Electric Bus	€/vehicle	464,745	444,219	401,155	317,945	308,555	298,577	293,964	294,703
Electric Bus with Diesel range extender	€/vehicle	312,742	305,126	295,527	281,654	280,281	278,831	278,158	278,254

Appendix A 2
Low Learning Cost Assumptions

Low Learning-Cost Assumptions	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Cost Batterypack	$/kWh	350	270	180	175	150	125	125	125
Conversion Rate	€/$	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Cost Batterypack	€/kWh	304	235	157	152	130	109	109	109
Electric Cars	€/vehicle	49,589	48,758	46,337	46,722	45,927	44,991	45,341	45,690
Electric Cars with Gasoline range extender	€/vehicle	47,093	45,854	44,512	44,050	43,791	43,533	43,533	43,533
Electric Cars with Diesel range extender	€/vehicle	49,743	48,461	47,075	46,569	46,310	46,052	46,052	46,052
Electric Cars with Natural gas range extender	€/vehicle	55,563	54,075	52,483	51,772	51,486	51,200	51,172	51,145
Electric Cars with Ethanol range extender	€/vehicle	53,304	51,883	50,358	49,713	49,434	49,155	49,135	49,115
Electric Truck with Gasoline range extender	€/vehicle	48,744	46,872	44,600	44,241	43,716	43,161	43,238	43,315
Electric Truck with Diesel range extender	€/vehicle	50,488	48,588	46,286	45,899	45,374	44,818	44,895	44,973
Electric Truck with Natural gas range extender	€/vehicle	53,891	51,777	49,261	48,660	48,106	47,522	47,571	47,620
Electric Truck with Ethanol range extender	€/vehicle	50,488	48,588	46,286	45,899	45,374	44,818	44,895	44,973
Electric Bus	€/vehicle	464,745	444,219	401,155	413,027	395,419	376,638	379,572	382,507
Electric Bus with Diesel range extender	€/vehicle	312,742	305,126	295,527	295,388	292,794	290,047	290,429	290,810

Appendix A 3
High Learning Cost Assumptions-Longer Hedging Period

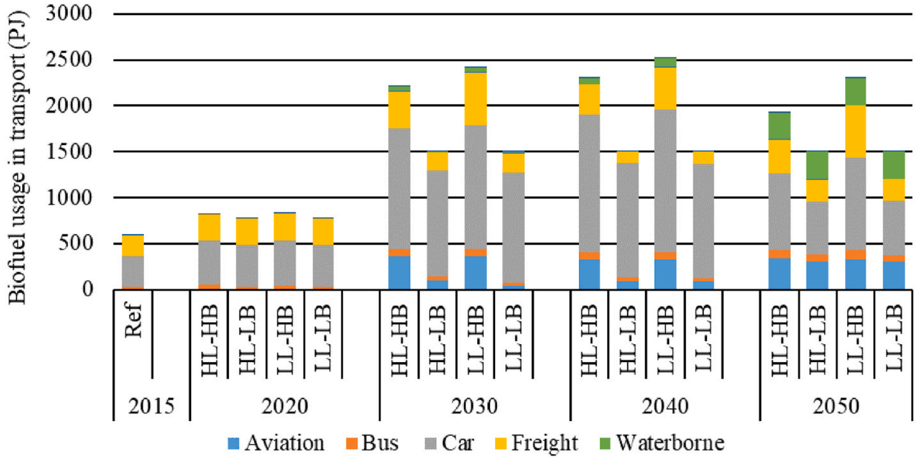
High Learning-Cost Assumptions-Longer Hedging Period	Unit	2015	2020	2025	2030	2035	2040	2045	2050
Cost Batterypack	$/kWh	350	270	180	175	150	37.5	31.5	31.5
Conversion Rate	€/$	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Cost Batterypack	€/kWh	304	235	157	152	130	33	27	27
Electric Cars	€/vehicle	49,589	48,758	46,337	46,722	45,927	40,250	40,012	40,101
Electric Cars with Gasoline range extender	€/vehicle	47,093	45,854	44,512	44,050	43,791	42,627	42,565	42,565
Electric Cars with Diesel range extender	€/vehicle	49,743	48,461	47,075	46,569	46,310	45,146	45,084	45,084
Electric Cars with Natural gas range extender	€/vehicle	55,563	54,075	52,483	51,772	51,486	50,294	50,205	50,177
Electric Cars with Ethanol range extender	€/vehicle	53,304	51,883	50,358	49,713	49,434	48,250	48,167	48,147
Electric Truck with Gasoline range extender	€/vehicle	48,744	46,872	44,600	44,241	43,716	40,890	40,754	40,774
Electric Truck with Diesel range extender	€/vehicle	50,488	48,588	46,286	45,899	45,374	42,548	42,412	42,431
Electric Truck with Natural gas range extender	€/vehicle	53,891	51,777	49,261	48,660	48,106	45,252	45,087	45,078
Electric Truck with Ethanol range extender	€/vehicle	50,488	48,588	46,286	45,899	45,374	42,548	42,412	42,431
Electric Bus	€/vehicle	464,745	444,219	401,155	413,027	395,419	298,577	293,964	294,703
Electric Bus with Diesel range extender	€/vehicle	312,742	305,126	295,527	295,388	292,794	278,831	278,158	278,254

APPENDIX B

Appendix B 1
Calculation of biomass bound in Low Biomass SOW

Pathways [13]	Total final energy consumption – transport (PJ) in 2020	Renewable Energy Directive target for renewable share	Minimum amount of biofuels according to target	Between 2% and 3% margin on the target, maximum biomass amount in Low Biomass SOW
Coalitions for a Low-carbon future	12,633	10%	1263	1500
Local Solutions	11,567	10%	1157	1500
Paris Agreement	12,627	10%	1262	1500

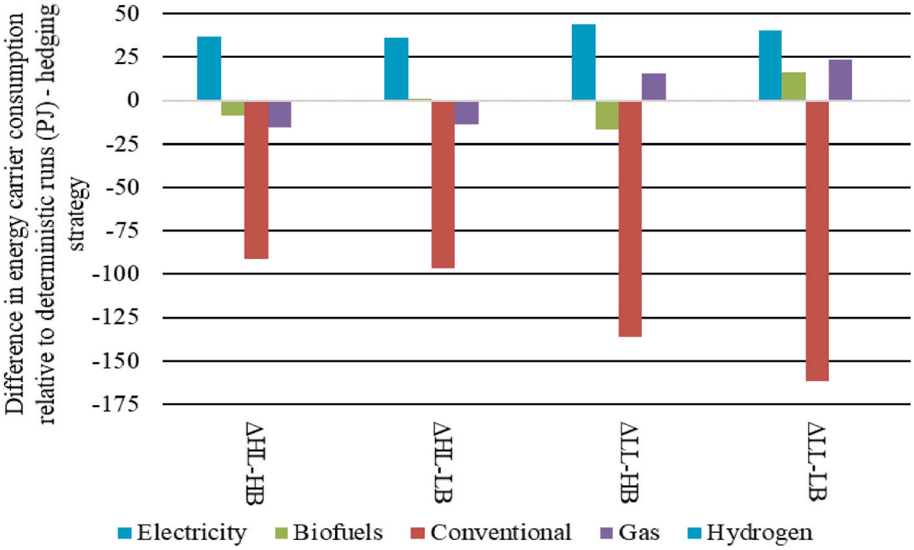
APPENDIX C



Appendix C 1. Biofuel usage in transport (without international aviation and waterborne) in 90% reduction target – Deterministic sensitivity analysis

Appendix C 2
Amount of biofuel and electricity in road transport in 2050 (PJ) – Deterministic sensitivity analysis

2050	80% Reduction Target		90% Reduction Target	
	Biofuel (PJ)	Electricity-Road transport (PJ)	Biofuel (PJ)	Electricity-Road transport (PJ)
HL-HB	2242	1357	1926	1918
HL-LB	1500	1479	1500	2092
LL-HB	2737	766	2301	1504
LL-LB	1500	876	1500	1720
Δ max H vs. L	1237	603	801	414



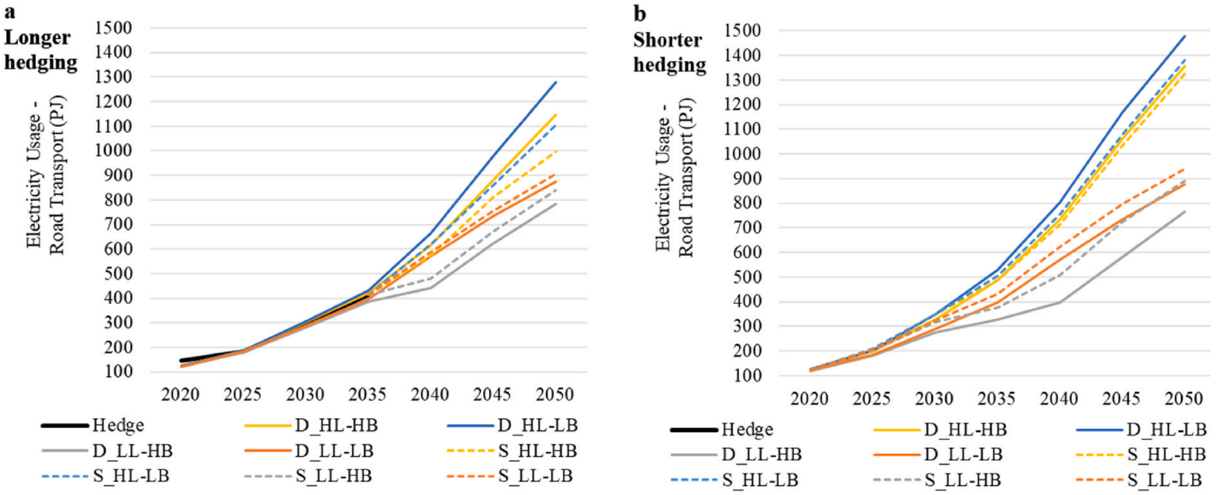
Appendix C 3. Difference in different energy carriers' consumption relative to deterministic runs - Hedging strategy in 2020 (as a representative year for the period between 2018 and 2022) in 80% reduction target

Appendix C 4
Amount of biofuel and electricity in road transport in 2050 (PJ) – Stochastic analysis

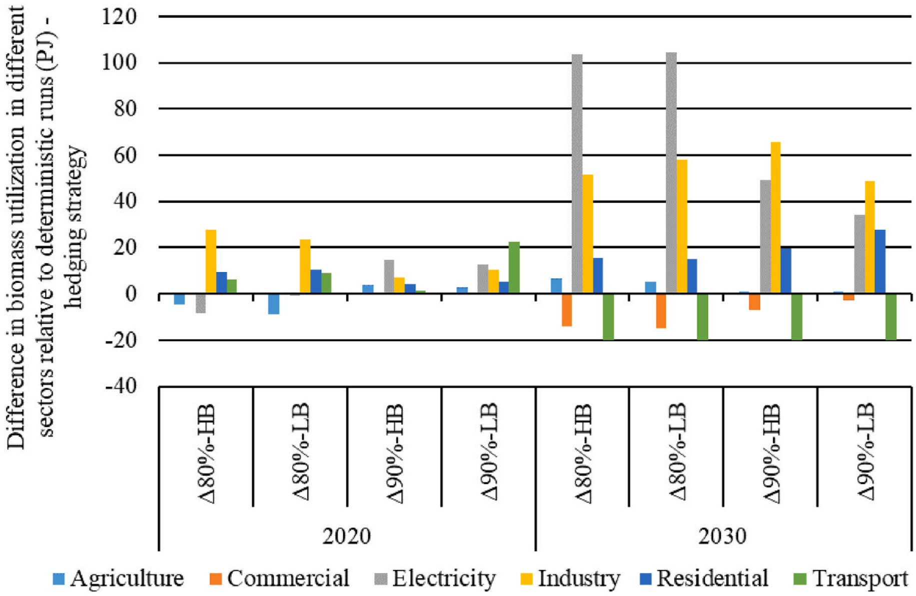
2050	80% Reduction Target		90% Reduction Target	
	Biofuel (PJ)	Electricity-Road transport (PJ)	Biofuel (PJ)	Electricity-Road transport (PJ)
HL-HB	2163	1327	1846	1896
HL-LB	1500	1381	1500	2060
LL-HB	2492	889	2109	1586
LL-LB	1500	941	1500	1768
Δ max H vs. L	992	438	609	310

Appendix C 5
Amount of biofuel and electricity in road transport in 2050 (PJ) – Longer hedging deterministic and stochastic analyses with 80% reduction target

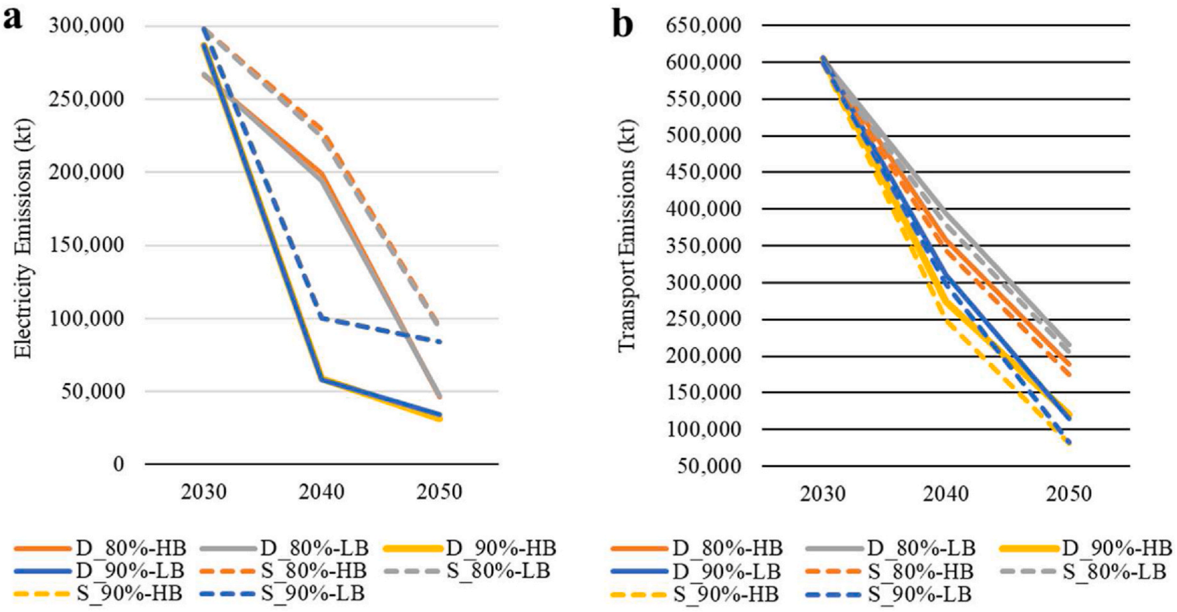
2050	Biofuel (PJ)		Electricity-Road transport (PJ)	
	Deterministic	Stochastic	Deterministic	Stochastic
HL-HB	2374	2346	1069	918
HL-LB	1500	1500	1202	1025
LL-HB	2667	2552	719	776
LL-LB	1500	1500	810	840
Δ max H vs. L	1167	1052	392	185



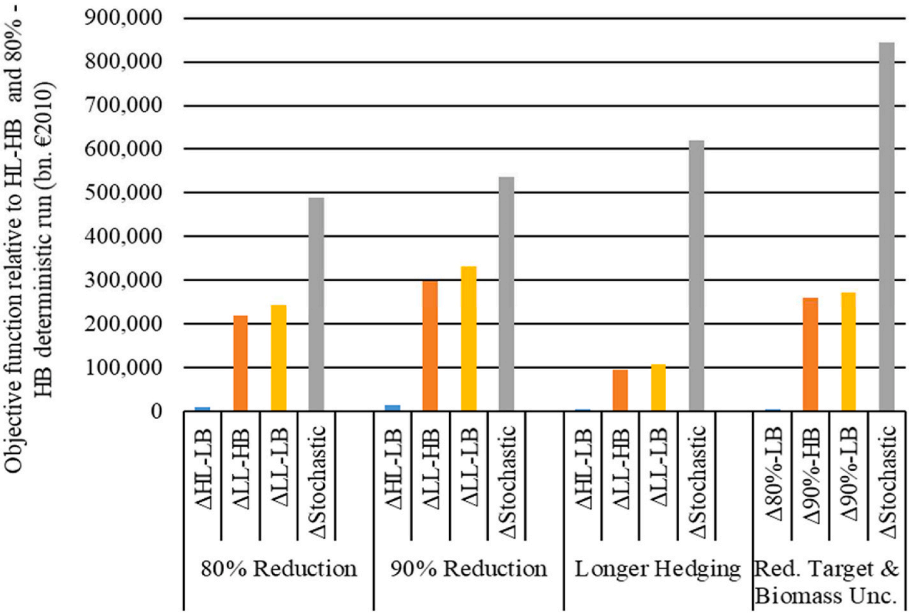
Appendix C 6. Electricity consumption road transport – Longer vs. Shorter hedging period



Appendix C 7. Difference in biomass utilization in different sectors relative to deterministic runs with High Learning for EVs (PJ) - Hedging strategy

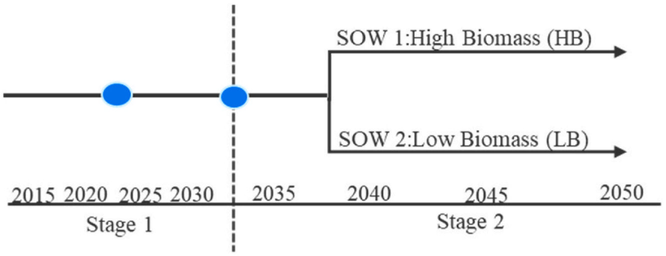


Appendix C 8. Electricity and transport emissions in Recourse period



Appendix C 9. Objective functions across the analyses relative to HL – HB and 80% – HB deterministic runs (bn. €2010)

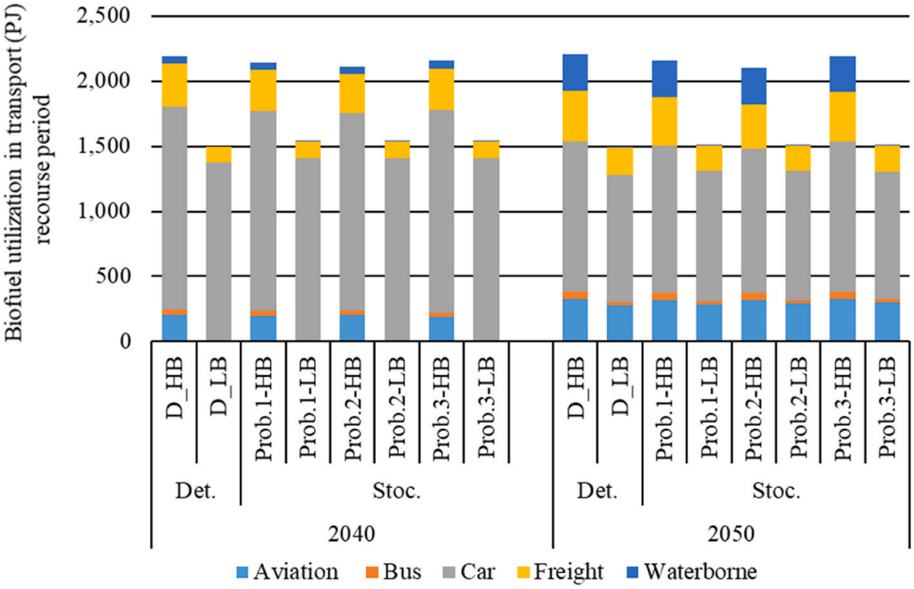
APPENDIX D



Appendix D 1. Stochastic scenario tree – probability analysis

Appendix D 2
Probability analysis - Scenarios and the probabilities

Stochastic analysis –Name of the scenario	High Biomass	Low Biomass
Probability 1 (Base)	50%	50%
Probability 2	20%	80%
Probability 3	80%	20%



Appendix D 3. Biofuel utilization in transport sector (PJ) – Recourse period

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4 Summary of the Results and Conclusions

4.1 Summary of the Research

In this thesis, the objective was divided into two main parts, as stated in Section 1.2. The first objective was to create an integrated assessment framework that considers the environmental and macro-economic variations in the energy system analysis through the energy transition in the EU to fill the relevant gaps in the contemporary research as elaborated in Section 1.4. The first step was to create an integrated assessment framework by integrating the macro-economic variations and air pollution control in the energy system modeling to fulfill this objective. TIMES PanEU was the integrated assessment framework's main structure, as an energy system model, and further linked with a health impact assessment model and a general equilibrium model. The first step in creating the integrated assessment framework, the Reference and GHG reduction scenarios, defined in [114], were performed with the calibrated TIMES PanEU model as explained in Section 2.3.1. In the GHG reduction scenario, 85% reduction was aimed based on the level of GHG emissions in 1990 in the EU28 as a whole. The GHG reduction scenario was also modeled after the introduction of the damage costs of the pollutants. The introduction of the damage costs in TIMES PanEU was realized with the link to a health impact assessment model, EcoSense, explained in Section 2.4.1. Next, the macro-economic variables' changes due to the energy transition were integrated into the energy system model. The link between TIMES PanEU and NEWAGE was created in the next step. Through the link, TIMES PanEU provided the electricity generation mix to NEWAGE. In return, NEWAGE delivered developments of the economic variables such as GDP and sectoral production to TIMES PanEU to be reflected on the energy service demand figures, described in Section 2.4.2. The sectoral developments from the NEWAGE results were reflected on TIMES PanEU energy service demand figures according to the technology matches between the models in Table 1. As there are other factors such as population and welfare that affect the energy service demand developments during the modeling horizon, a decoupling factor was applied to consider these parameters on the demand development. Due to the feedbacks between the models, an iteration process was carried out until the convergence criteria was achieved [114]. Decomposition analysis was employed after the integrated assessment framework was structured to understand these drivers' contributions to the system's decarbonization. The analysis was carried out further for a detailed pathway assessment to examine the impacts of the air pollution control in the energy system in case of high renewable share in [114] with the methodology introduced in [114].

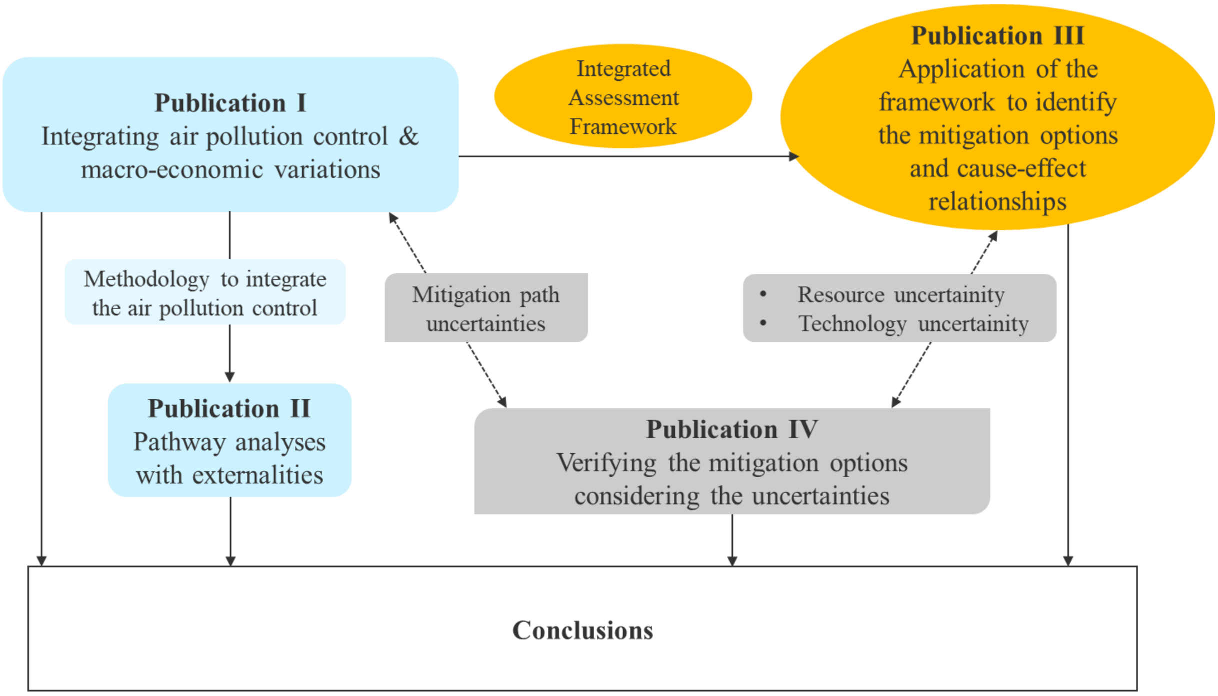

Figure 8: Relative relationship between Publications based on the feedbacks

The next step in this research was to address the second research objective, identifying the mitigating options' role, stated in Section 1.2. The integrated assessment framework, which was created by linking the three models [114], was applied for a pathway analysis with different reduction targets in various sectors and a diverse technology mix. Although decarbonization pathways had been studied in the contemporary research, based on the literature review in Section 1.3.2., the need to assess the cause-effect relationships in the energy system was identified as elaborated in Section 1.4. Additionally, such an analysis had not been delivered yet considering the externalities and the impact of macro-economic variations in the energy system at the EU level which this thesis brings as an additional novelty to the contemporary research. The integrated assessment framework was employed to study three deep decarbonization pathways as part of this thesis to fill these gaps, stated in Section 1.4. The decoupling factor was determined as 66% to reduce the macro-economic variations' feedback by focusing on the pathway analysis. As described in Section 2.5., pathways were structured according to different storylines. These storylines supported the assumptions' rationalities to explore the potential dynamics during the decarbonization of the energy system.

In Coalitions for a Low Carbon (CL), it was assumed that the industry sector mainly carried out the decarbonization burden. Simultaneously, decentralized mitigation options such as heat pumps and building-integrated solar PV were made available only to a limited extent. On the other hand, in Local Solutions (LS), the decarbonization motivation came from society to reflect the approach in [8], “consumers are at the heart of transition”. Therefore, the availability of centralized mitigation options such as carbon capture storages (CCS) and nuclear was restricted to only scheduled projects. They were not defined as technology options for future investments. Moreover, transport and residential were expected to reduce their emissions further by taking the burden from other sectors. Those two pathways aimed to achieve an overall 80% GHG reduction in the European energy system in 2050 according to the level in 1990. In the Paris Agreement (PA) pathway, in which the aim was to achieve a 95% reduction, all the technology options, including biomass CCS became available for future deployments.

Finally, by considering the feedbacks from the decomposition analysis and the pathway assessment to verify the mitigation options' role as stated in Section 1.2, the impact of uncertainties in the transport sector development was studied by employing stochastic programming in TIMES PanEU. The uncertainties might actually provide different insights to the findings from the energy transition analysis so far, as discussed in [70, 88, 91] considering the exogenously defined technology assumptions. Therefore, uncertainty assessment was also included in this thesis's scope as part of the second research objective, as described in Section 1.2. Based on the analysis in [114], the transport sector was acknowledged as the hardest to decarbonize between the non-ETS sectors by considering macro-economic and environmental perspectives through the energy transition. The transport sector is the only sector that did not reduce GHG emissions since 1990 [3]; the emissions have actually increased since then. According to the decomposition analysis in [114], electric vehicles and biofuels were identified as the main mitigation options. Additionally, pathway analyses in [108], in which the findings were presented as a part of this thesis, showed that biomass could be utilized in different parts of the energy system. The potential of the resource needs to be optimized across the sectors considering different decarbonization paths. Cost reduction paths for the mitigation technologies could create different trends, as seen with the breakthrough cost reduction scenarios in [108] as well. The findings in [114, 115, 109] showed that different reduction targets to reduce GHG emissions might bring different insights for the development of the energy system during the transition. Therefore, uncertainties around the mitigation options for the specific sectors as well as different GHG reduction targets in the energy system could cause further sectoral developments. In [115], the uncertainties around the sector-specific biomass potential and cost of electric vehicles and their criticality for the decarbonization in the transport sector considering different GHG reduction targets were addressed to finalize the second research objective as stated in Section 1.2.

As explained in Section 1.5., the assessments were realized in 4 inter-related Publications [114, 115, 109, 116] , schemed in Figure 8. In the second part of this Chapter, the focal results are summarized, and the integrated conclusions are stated.

4.2 Integrated Conclusions

This section brings together the 4 inter-related publications' insights to address this thesis's research questions as drafted in Section 1.2. by consolidating the findings explained and discussed in [114, 115, 109, 116]. The scenarios carried out in [114, 115, 109] as part of the analysis are given in Table 5 with the abbreviations.

Table 5: Scenario Table

Publication Order	Name of the Scenarios	Description
Publication I	Reference	Business as Usual (EU Reference Scenario)
Publication I	GHG	85% GHG reduction in the EU and health damage costs are not internalized as part of the optimization function
Publication I	GHG_DAM	85% GHG reduction in the EU and health damage costs are internalized as part of the optimization function
Publication I	IAT_25	85% GHG reduction in the EU and health damage costs are internalized as part of the optimization function, coupled with macro-economic model with 25% decoupling factor
Publication I	IAT_50	85% GHG reduction in the EU and health damage costs are internalized as part of the optimization function, coupled with macro-economic model with 50% decoupling factor
Publication I	IAT_75	85% GHG reduction in the EU and health damage costs are internalized as part of the optimization function, coupled with macro-economic model with 70% decoupling factor
Publication II	Base	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States;
Publication II	Base_DAM	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States; health damage costs are internalized as part of the optimization function
Publication II	HighRES	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States; 75% share of Renewable in the final energy consumption in 2050 considering country clusters;
Publication II	HighRES_DAM	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States; 75% share of Renewable in the final energy consumption in 2050 considering country clusters; health damage costs are internalized
Publication III	Coalitions for a Low Carbon Path (CL)	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States; supply driven transition is aimed

Publication III	Local Solutions (LS)	83% decarbonisation target for the ETS sectors in the EU as a whole in 2050, compared to 2005 levels; Ambitions on non-ETS sectors different by clusters of Member States; demand driven transition is aimed
Publication III	Paris Agreement (PA)	95% decarbonisation target across all sectors in the EU as a whole in 2050, compared to 1990 levels

An integrated assessment framework for the energy system analysis that considered the environmental and macro-economic feedback loops entailed additional findings during the energy system's decarbonization concerning the first research objective in Section 1.2. The existing TIMES PanEU model was further linked to a health impact assessment model and a macro-economic model to incorporate the feedback loops from the environment and economy into the energy system. This process was carried out between the models through a soft-link process. High level of transparency, high level of traceability, required flexibility, and user-control modifications when required became possible as first of its kind, enlightened in Section 1.4. During the process, iteration was not necessary between TIMES PanEU and the health impact assessment model, Ecosense. Due to the linear relationship between the total health damage costs as calculated by EcoSense and the total emissions, the unit costs are independent of the absolute amount of emissions and climate mitigation policies.

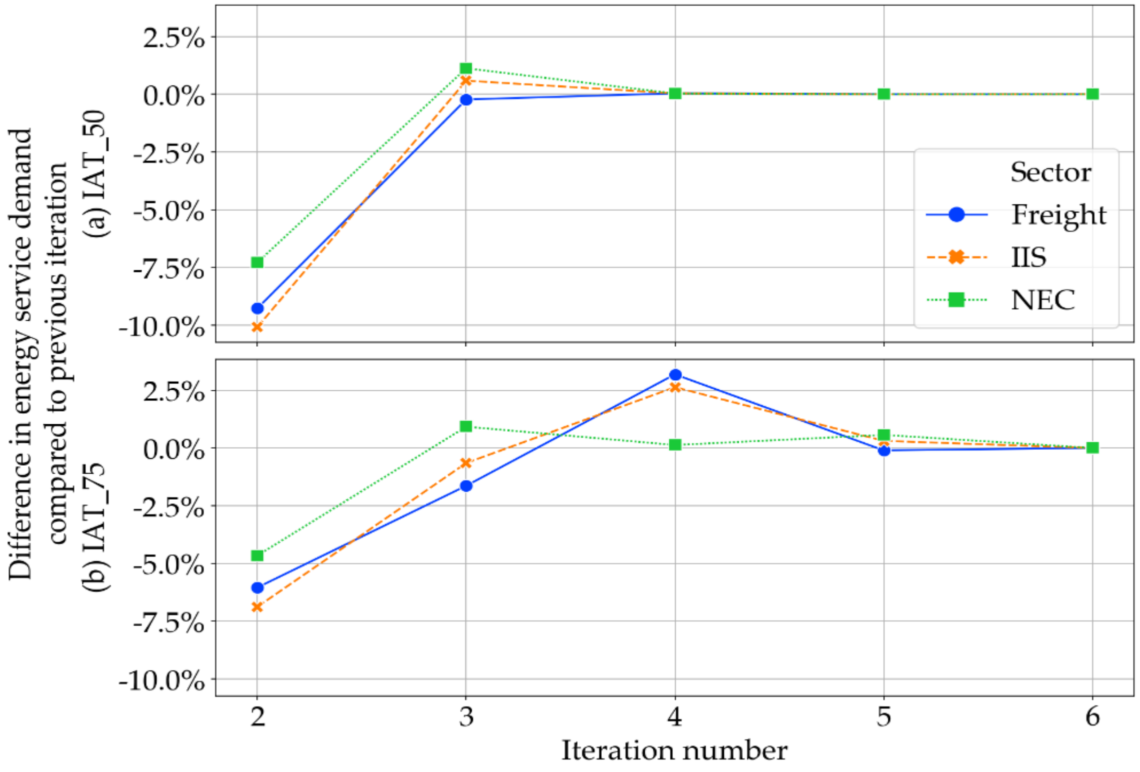

Figure 9: Difference (%) in the selected energy service demand developments in the EU28 compared to the previous iteration for (a) IAT_50 and (b) IAT_75 in 2050 **[114]**

The link was iterative between TIMES PanEU and the macro-economic model, NEW-AGE, because of the mutual feedbacks concerning the first research objective in Section 1.2.

As explained in Section 2.4.2, the decoupling factor was defined to reflect the other socio-economic parameters' developments since other factors also affect the energy service demand projections. A specific methodology was not developed to define a decoupling factor within the scope of this thesis. Therefore, a sensitivity analysis was conducted to assess the impacts of having different decoupling factors during the iteration process – 25% (IAT_25), 50% (IAT_50), and 75% (IAT_75) – as an additional novelty of this thesis to the contemporary research as elaborated in Section 1.4. The analysis with varying decoupling factors showed that the decoupling factor affects the convergence values and the iteration process. The iteration process needed fewer iterations for a decoupling factor of 50% or less (Figure 9). However, this resulted in a higher variation on the convergence values. On the other hand, the iteration process took longer if the decoupling factor is higher than 50%, while the variation of the convergence values was smaller than the lower decoupling factors. The lower the decoupling factor, the tighter the links between the models, and they have more feedbacks from the developments in each mode. Since both models reacted fast enough to the system's changes due to a higher level of feedback, the number of iterations was also reduced during the processes. In the case of a higher decoupling factor, the data exchange was kept limited. As a result, there was a less intense exchange between the models, and it took more time for the models to react to the system's modifications. Therefore, it lasted longer for both models to settle.

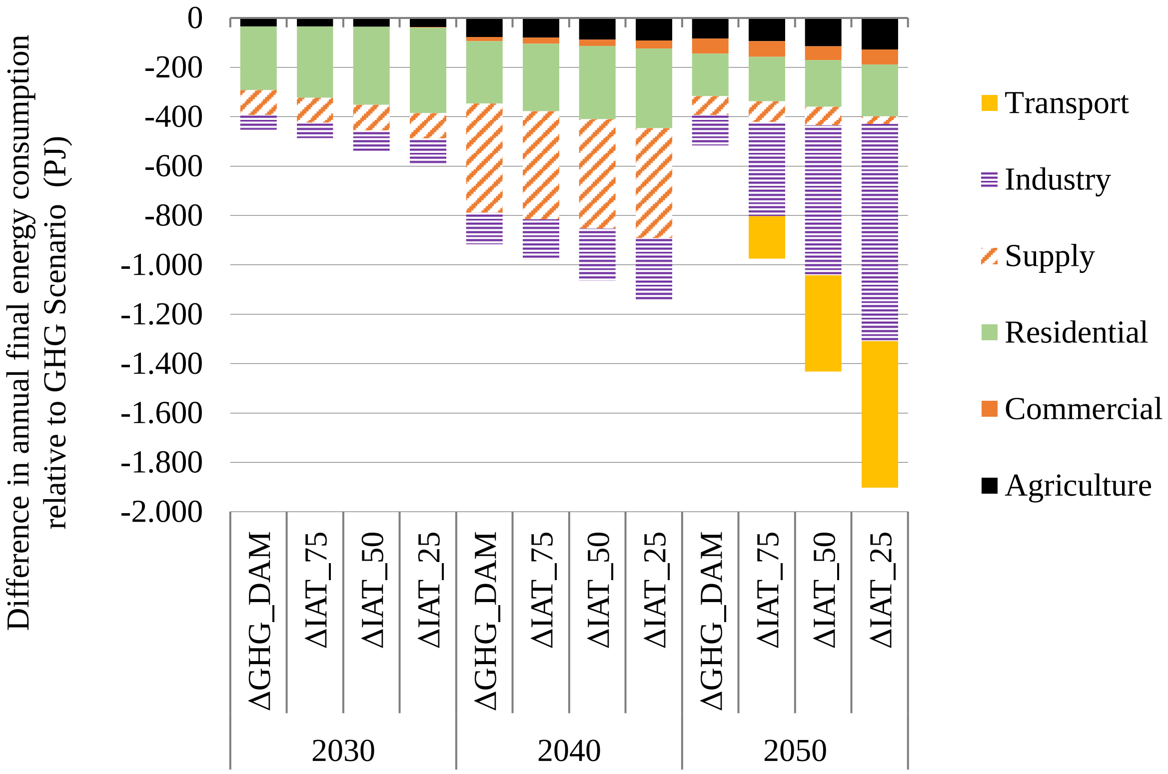

Figure 10: Difference in annual final energy consumption by sector relative to GHG_DAM scenario in the EU28 (PJ) **[114]**

Internalizing the air pollution control and the responses of the economy to the energy transition reduced the overall final energy consumption in the EU by investing in more efficient technologies to respond the air pollution control in the mid-term. Integration of macro-economic effects reasoned the demand reduction, especially in the industry and public transport sectors which also reduced the final energy consumption in those sectors (Figure 10). Macroeconomic feedbacks also decreased the need for structural change during the energy transition, according to the decomposition analysis results in [114]. On the other hand, air pollution control integration slightly increased the need for structural changes such as investing more in renewables. As the focus was also on the electricity sector during the coupling process, this reduced need for the structural change became more visible with the reduction of renewables; in total 1.300 PJ with 25% decoupling factor.

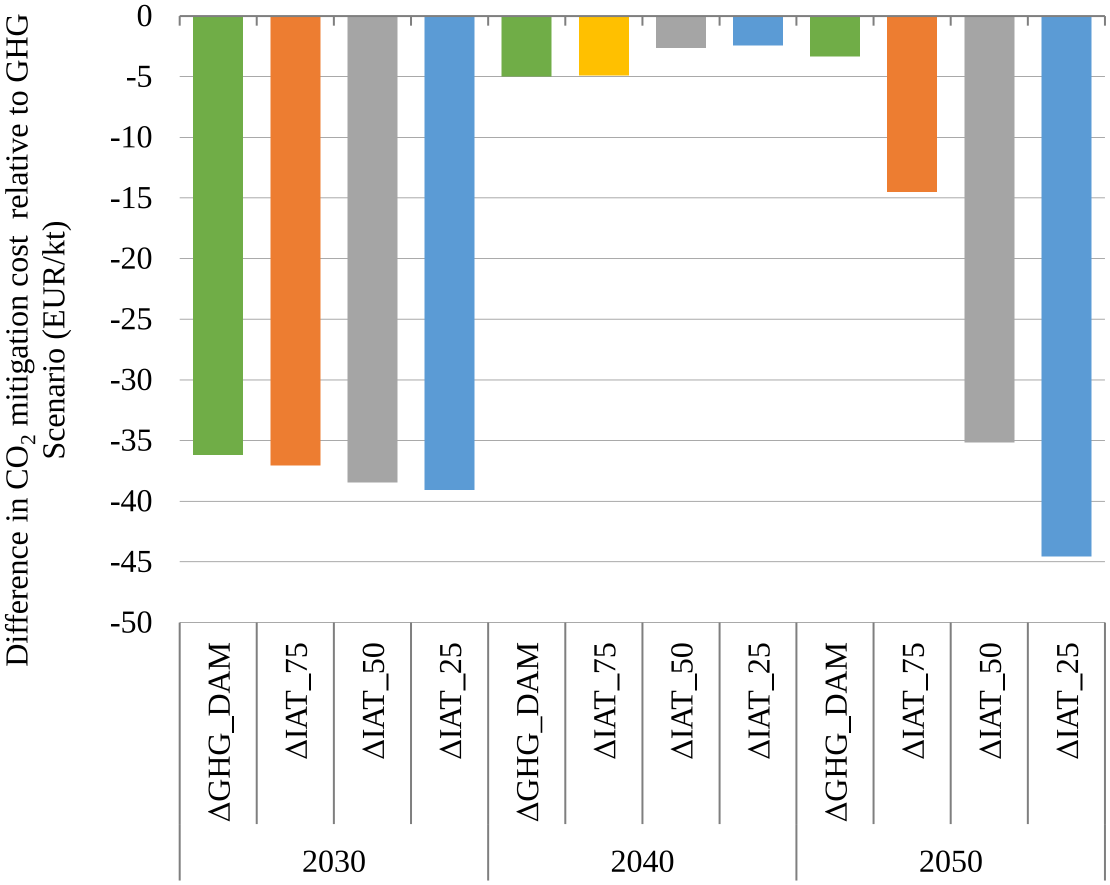

Figure 11: Difference in CO_2 marginal mitigation cost relative to GHG Scenario in the EU28 (€/kt) **[114]**

Additionally, integrated analysis shrank the CO_2 mitigation costs at the EU level to achieve the energy transition. Introduction of the air pollution control by internalizing the damage costs in the energy system brought a cost-optimal solution to maximize the social welfare and takes the burden from the CO_2 mitigation by sharing the cost-effective co-benefits. In this way the total social costs were minimized, and the social welfare was maximized. The CO_2 mitigation costs were reduced further since the burden again was shared with the demand response due to the macro-economic effects. Therefore, the integrated view also reduced the need for higher system integration for the energy transition. Considering the required short-term and long-term actions, integrated assessment with environmental and macro-economic feedbacks brought complimentary benefits. Air pollution control by internalizing the damage costs helped the system reduce mitigation costs in short to mid-term (Figure 11). As TIMES PanEU minimizes discounted total cost with perfect foresight, reducing expenditures in the first years is of greater value than reducing them in later years. These findings highlighted the importance of the integrated view and benefits of having an integrated assessment framework concerning the additional novelties discussed in relation to the firs research question in Section 1.4. The integrated view reduced the overall burden in the energy system due to the energy transition, with air pollution control in short to mid-term and macro-economic feedback the long term.

Various energy system sectors reacted contrarily to air pollution control and macro-economic feedback at different periods. The residential sector was mainly affected by these parameters in short to mid-term. As one of the novelties of this thesis elaborated in Section 1.4., it was possible to capture the macro-economic feedbacks also on this sector. Integration of air pollution accelerated the coal-phase out in the mid-term, which means decarbonization can also occur in the early periods. It incentivized the early deployment of more efficient renewable technologies such as solar heaters & heat pumps in relation to the second research objective in Section 1.2. Additionally, according to the economic structure defined in NEWAGE, the revenues to the households from emission certificates were paid in the late periods. The residential sector in this structure could benefit from the energy transition in the long term and did not need to reduce welfare. However, the sector was not incentivized in the short and mid-term for the energy transition. Thus, only slight demand reductions were also seen in this period.

The industry sector benefited the most from the macro-economic changes during the energy transition due to the demand response in this sector. Especially in the long-term, when the decarbonization targets become more ambitious, it required more intensive structural changes that might be costly for the economy as a prominent fossil fuel consumer. With the help of the demand response, it reduced the need for structural change. Like the residential sectors, air pollution control also reasoned the early phase-out of coal in the energy mix. Between the energy system sectors, the industry was identified as the hardest to be decarbonized. There is still a need for technological developments for further reactions and balanced economic feedback.

Electricity generation was expected to increase during the energy transition, bringing structural changes in the energy system. Integration of macro-economic parameters helped to balance the required high electricity generation by reducing renewables in the electricity sector. Internalization of air pollution control reorganized the CCS deployment from fossil fuels in the long-term by reducing the share of the technology in the countries where it is still allowed and increasing the renewable deployment. Biomass utilization in the sector was also affected by the environmental damages in the optimization. Since the most mature mitigation options are available and the direct use of renewables is also mostly possible only in this sector, it also plays a role directly in the other energy system sectors. The need for electricity was directly increased in a particular sector if there is a specific and higher decarbonization target. Offshore wind can be a game-changer technology to reach the required generation with the higher capacity factor compared to solar and on-shore wind technologies concerning the second research objective in Section 1.2. Although centralized technologies such as nuclear and fossil CCS technologies are expected to be part of the technology mix in most of the scenario analyses, with the available potential of wind and solar, it is also possible to carry out an energy transition with a decentralized technology mix without further deployment of nuclear and CCS technologies such as in Local Solutions pathway in [108]. On the other hand, fossil-fueled CHP CCS technologies can provide heat to residential and industry sectors. In the case of a centralized energy transition, the deployment of these technologies and a higher share of heat in those sectors might be expected through the system's decarbonization. Since the mitigation technologies have already experienced the learning in this sector, these technologies will be deployed through the energy transition. Therefore, a high level of uncertainty is not expected for the cost reduction of the technologies and the impact of the cost development on the deployment. Although it has the most mature mitigation technologies, the sector cannot react fast enough to the uncertainty that concerns the entire system, such as policy. In this case, the electricity sector preferred the wait-and-see approach instead of acting in the short or mid-term. The wait-and-see approach can also slow down the mitigation options' deployments after the uncertainties are resolved in the system. The long lifetime of technologies in this sector makes it harder to react fast enough for the uncertainties. Therefore, the burden-sharing structure can be altered between the electricity and other sectors in case of such uncertainty.

The utilization of biomass was affected across the sectors as an energy source with air pollution control in the energy system, although it was not affected significantly by the macroeconomic feedback. In the residential sector, the use was reduced in the early periods. However, in the late periods, independent of the air pollution control in the optimization, the utilization was already shifted to other sectors. Direct use of solid biomass can create a conflict in the energy system between the air pollution control and high renewable share target. As solid biomass can be directly used in residential and industry sectors, air pollution control can hamper the utilization in these sectors, and the focus can be shifted to a sector like transport. In this sector, compared to others, biomass utilization can be more environmental-friendly. Modern biofuel cars have the same emission levels due to road abrasion, tire & brake wear. Availability of negative emission technologies, such as biomass CCS in the electricity sector, can also completely change the utilization with a higher reduction target in the energy system, such as in Paris Agreement pathway [108]. Biomass utilization in the system were also affected by the sector-specific reduction targets. For example, if the energy system is forced to have a higher decarbonization target in the transport sector, the energy carrier's share with the use of biofuels can be increased in this sector (Figure 12).

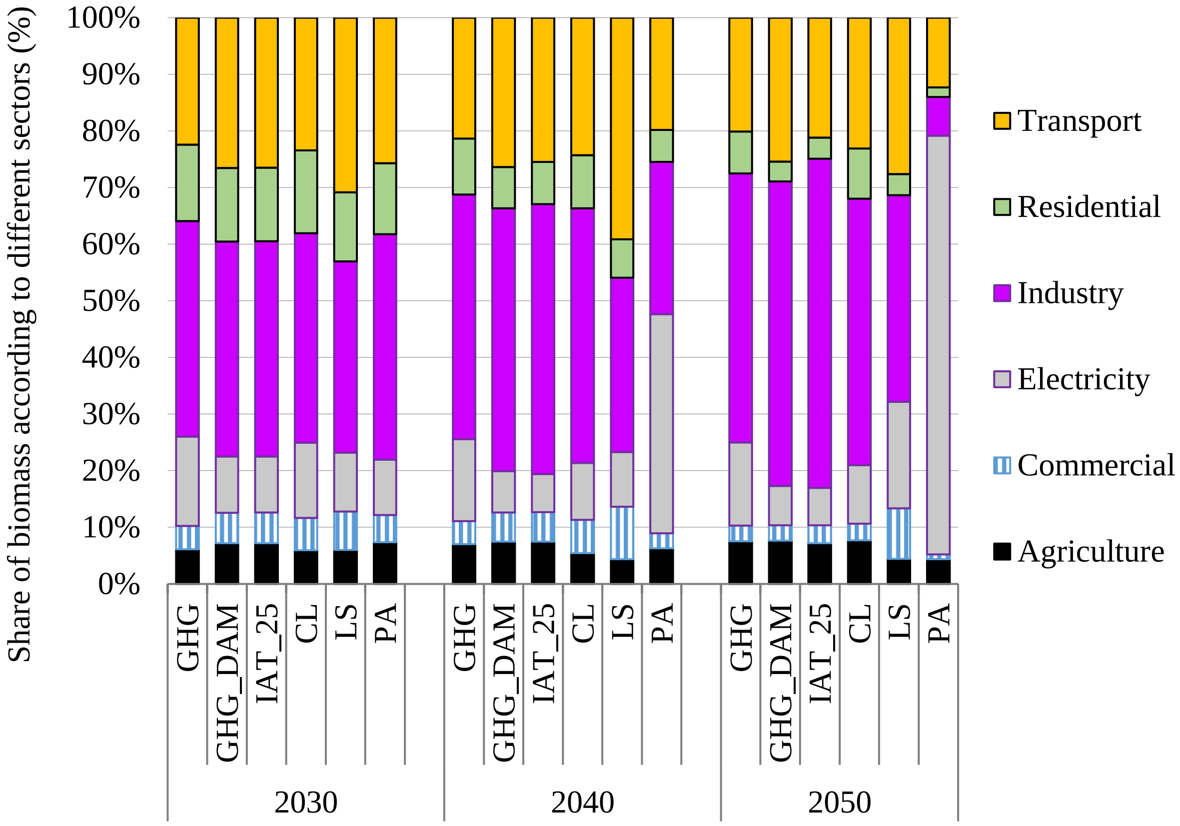

Figure 12: Share of biomass according to sectors (%)

Early reductions of SO_2 and NO_X emissions were experienced in the energy system when the air pollution control became part of the optimization as a result of the integrated view mainly because of early coal phase-outs in residential, agriculture, and industry sectors and lower application of the gasification processes in the supply sector concerning the first research question in Section 1.2. $PM_{2.5}$ and PM_{10} emissions were reduced thanks to fuel switches in the transport sector. Again $PM_{2.5}$, PM_{10}, and NO_X emissions were also declined in the electricity sector thanks to the higher integration of renewables. SO_2 and NH_3 emissions were the most challenging ones to be reduced after a certain level since they were mainly emitted in industry, and the options were somewhat limited in this sector. Although air pollution control helped the system decrease pollutants in the early periods, in the long-term GHG reduction target itself became a decisive factor. Higher reduction targets beyond 80% also brought higher declines with the pollutants, demonstrating the trade-off in between.

According to the assessment in [114], transport was identified as the most challenging sector to be decarbonized between the NON-ETS sectors. The transport sector was highly vulnerable to economic changes. Especially the energy service demand such as freight and public transport, which are currently heavily dependent on fossil fuels, were responsive to economic feedback. Therefore, demand response can have a significant role in the decarbonization of the sector in the long-term. Although electric vehicles and biomass are the main mitigation options, macroeconomic feedback reduced the need for higher system integration concerning the first research question Section 1.2. As mentioned, biomass utilization in this sector can still be environmental-friendly, and even with air pollution control, the source can still be widely applied as a mitigation option in relation to the second research objective in Section 1.2. Availability of biofuels will also be important in aviation and navigation. Especially not only for the decarbonization but also for the further reductions of the SO_2, which is emitted highly in aviation and navigation, biodiesel and bio-kerosene will be required for these transport modes. Although EVs are seen as the most promising mitigation option in the sector, they carry the uncertainty, especially with the projected cost reductions for the batteries in their system. Another mitigation option was identified as biomass, but it is not clear how this source would be utilized across the sectors. The further assessment was carried out to verify their roles during the transition with stochastic programming as part of the second research objective stated in Section 1.2. The results of the analysis showed that earlier deployments of the EVs in the system to hedge the cost reduction uncertainties will be essential. Again, the outcomes demonstrated that if the technology's cost reductions are postponed, the deployment can be even lower than expected, considering the uncertainty in the analysis with stochastic programming. The wait and see approach instead of immediate actions could also be costlier to the system, additional to lower deployments. However, even if the cost reductions were postponed, early deployments were required to hedge the relevant uncertainty. Since the EVs are also more efficient than conventional vehicles, the early deployments brought efficiency advantages and early declines in the final energy consumption. In case of limited biomass availability in the system, car transport was prioritized for utilization [116], and even if the biofuels became available for the navigation sector, the first place belonged to car transport. The allocation of limited biomass was also dependent on the GHG reduction target in the system. When the reduction target became more ambitious in the system, a particular biomass amount was allocated to navigation to decarbonize this transport mode. The cost uncertainty with the EVs became even less relevant in high-reduction scenarios to balance the reduced biofuels in car transport, which surged deployment of EVs. Policy became the decisive factor again for the system, not the uncertainty itself. Therefore, EVs are identified as one of the no-regret options during the energy transition in case of higher policy targets beyond 80% in the EU. Early deployments could help hedge the given uncertainties in the system and support the early cost reductions, considering the technology's role as a no-regret option. With the advantage of having a lower lifetime of the technologies, the transport sector could also play a compensation role if there is uncertainty, such as policy which concerns the entire system. In the analysis in [116], the sector reacted before the uncertainty is resolved since it responded fast enough to the given uncertainties. It took the electricity sector's burden since the sector did not act fast enough, which means that early deployment of mitigation technologies such as EVs again can also be a measure for the policy uncertainties.

5 Discussion & Outlook

The aim of this thesis was to integrate the air pollution control, macro-economic feedbacks, and technology uncertainty into energy system analysis to verify the role of the selected mitigation technologies through the energy transition in the EU as stated in Section 1.2. This thesis had been carried out with four inter-related publications as explained in Section 1.5. The structure carried out in this thesis and findings are summarized in Section 4 to extract the integrated conclusions. Some of the findings require further assessment to pinpoint applications in the practical world. Besides, there are additional aspects which were not considered and/or integrated within the scope of this thesis but might add additional insights to the findings. Based on the presented work the following four main aspects are relevant for the discussion:

1. Integrated assessment framework
2. Macro-economic impacts
3. Stochastic analysis
4. Decomposition analysis

Integrated assessment framework was created in the first step by creating a link with a health impact assessment model to implement the damage costs in the energy system to consider the feedbacks with the air pollution control. The findings of the various analyses in this thesis indicated that there is a trade-off between GHG reduction target and air pollution control in relation to the first research objective in Section 1.2. Integrating the cost of the air pollution into the system accelerated the decarbonization in the short to mid-term by reasoning the early phase out of the coal across the sectors. Since TIMES PanEU aims to have a cost-optimal system according to foresight principle, it can postpone the certain decision until the cost of the mitigation technologies become competitive enough. Integration air pollution control into the energy system analysis can be a solution for the required short to mid-term actions. The early actions are also very critical considering the cost uncertainties with the mitigation technologies such as EVs which are still not mature. In the light of critical discussions of the biomass utilization and the conflict with the air pollution, incorporating the environmental aspects into the analysis, can assist for the optimum and environmental-friendly allocation of the source in the energy system. Although EU wide analysis have already highlighted the significance of the air pollution control in the energy system, air pollution is more concerned at the local level. Therefore, country-based analysis can bring further insights for the tradeoffs in between. The similar analysis with the applied methodology here can be carried out with the country energy system models. In this thesis, damage costs were disaggregated at the Member State level, but the sectoral disaggregation was not considered within scope. This can be also suggested as a further analysis, although it might increase the computational time of both models. As discussed in [128], there is also high range of uncertainty with the damage costs calculated in Ecosense which might convey additional findings. Since these uncertainties are related to the input assumptions to the models, as parametric uncertainties, they can be further assessed with stochastic programming to also address the impact of uncertainties.

Macro-economic impacts were incorporated to the energy system analysis through a soft linking with a macro-economic model within the scope of this thesis in relation to the first research objective in Section 1.2. Each energy service demand was able to receive the relevant feedback from the economy based on the electricity mix between two models. This analysis was carried out after the integration of air pollution control in TIMES PanEU. However, the macro-economic model, NEWAGE, did not take into account this trade off during the calculations. It is recommended to implement pollutants, and their damage cost into the macro-economic model structure to reflect the feedback between the economy and the environment as well.

Table 6: Decoupling factor analysis – Germany

Germany		Statistics: Absolute Values [149]		Growth rates	Decoupling factor vs. GDP
Categories	**Years**	2000	2017	2000-2017	
Gross domestic product (GDP)		2555.609	3174.16	1.28%	
Inhabited living space (million m^2)		3,234	3,699	0.79%	0.619
Passenger traffic in billion pers.-km		1,045.1	1.155,2	0.59%	0.461
Freight transport in billion tkm		511.3	692.6	1.80%	1.404
Production volume of nonferrous metals (kt)		5,174.6	5,431.8	0.29%	0.223
Production volume of steel (kt)		46,376.0	43,032.0	-0.44%	-0.342
Production volume of paper (kt)		22,146.6	26,763.3	1.12%	0.873
Average					0.539
Average without Steel					0.716

A decoupling factor was introduced for the macro-economic model's feedback on the demand development to reveal the relation between the demand development and other factors such as population and behavior as an additional novelty of this thesis as elaborated in Section 1.4. Sensitivity analysis was included in the scope for assessing the impacts of the decoupling factor on the iteration process and the demand development. It was concluded that the decoupling factor influences the convergence values as well as the iteration process. The relationship between the economic parameter, GDP, and energy service demand development between 2000 and 2017 was evaluated for the selected energy service demands to verify the assumptions for the applied decoupling factors in this thesis (Table 6). The GDP was determined as the main criteria to define the relation in between. The average value for the given categories presents that the values applied as decoupling factor in this thesis's scope are comparable with the reality. Economic developments had a higher impact on the industrial sector, iron and steel, in the same period as the average becomes higher when this sector is not taken into account. This relationship between the economy and the energy service demand also confirms the findings of the industry. Industrial sectors such as iron and steel and nonferrous metals are the main sectors influenced by the economic developments. However, the influence on the sectors such as residential heating or private transport is limited. Although the results of the analysis for the relation between economy and energy service demands confirm the findings of this thesis, it also identifies the need for a further study. A similar assessment can be carried out for each Member State for every energy service demand category, and decoupling factors can be calculated with a similar methodology for different Member States and integrated into the coupling process. The results might vary, especially on the country level. As an additional assessment, the uncertainty analysis can be carried out to deal with the uncertainty for the relation between economy and energy service demands. Since the demand assumptions are classified as parametric uncertainties, stochastic programming can be employed to have more realistic results for the impact of the economy on the energy system.

Stochastic analysis was carried out in this thesis's scope to verify the role of the mitigation options considering the relevant uncertainties as part of the second research objective. According to results, car transport is prioritized through the decarbonization of the transport sector. Since TIMES PanEU does not cover the behavior part in the structure, it is not possible to evaluate the role of the potentially changing behavior during the modeling horizon. For example, people would prefer to use more public transport instead of private transport if they were more cost-efficient than buying a new car. This integration might also influence the trade-off between air pollution control and transport sector decarbonization. In a further study, the analyses carried out in this thesis can be developed by integrating consumer behavior into the energy system to overcome this limitation. Since car transport is prioritized, electric vehicles will also be deployed, as discussed in Section 4.2. This deployment might be already accelerated in short to mid-term to hedge the given uncertainties. However, this analysis does not take into account the life-cycle emissions. The existing structure of TIMES PanEU can be further linked to a life cycle assessment model to consider these emissions in the analyses for the further development of the existing framework.

Thanks to stochastic programming, the given uncertainties have been integrated into the energy system analysis to develop hedging strategies to define the short to mid-term actions and recourse strategies with a two-stage stochastic tree without increasing the computational time heavily to verify the role of the technologies during the EU energy transition. Determining the number of the State of the Worlds and the number of stages is identified as a crucial step since a high number of SOWs could easily increase the computational time, which might not be worth the effort. On the other hand, the defined SOWs should cover the uncertainty range, and the number of stages shall be aligned with the foreseen timeline considering the analyzed uncertainties. This thesis focused on two main SOWs for each given uncertainty considering their likelihood and the uncertainty range to verify the role of the technologies in relation to the second research objective in Section 1.2. These SOWs were combined by taking into account the foreseen timelines for their resolution time based on the existing literature. Uncertainty range was also defined considering the minimum and maximum expected values for biomass and EV uncertainties. This approach can also be applied in different parts of the energy system in view of cross-sectoral dynamics to develop hedging and recourse strategies for the relevant uncertainties.

Mitigation technologies such as CCS, off-shore, and onshore wind technologies will need to be deployed to achieve a specific GHG reduction target based on the findings. Nevertheless, these technologies have been experiencing a social acceptance problem. Since they will be required in the transition, the social acceptance problem should also be integrated into the energy system analysis to identify the technologies' potential, also considering their role in society. This also could be integrated through the behavior and/or by introducing additional acceptance costs in the structure.

Stochastic programming was employed as addition to the traditional sensitivity analysis to develop potentially hedging and recourse strategies for the given uncertainties and confirm the role of the mitigation options in the transport sector. In the case of EVs, the results showed that the early deployment of such a promising technology is essential to hedge the cost uncertainty and policy uncertainty. Although the assessment was carried out for the future role of EVs, it can be concluded that for the other mitigation technologies such as hydrogen, the early investments can play a crucial role in achieving particular learning with the technology and advancing a better strategy development.

Stochastic programming can be applied in the energy system studies can provide the hedging and recourse strategies for the parametric uncertainties, which are defined as input assumptions. In this thesis, uncertainty assessment played a verifying role for the analysis. Since the number of uncertainties within the scope was limited, stochastic programming was chosen for the additional assessment. However, stochastic programming can also be very time-consuming if the number of given uncertainties is high. Therefore, it is crucial for the application to define the number of uncertainties and the resolution time. Later, it needs to be decided if it is worth the effort. The current stochastic programming application also requires the probability function for the likelihood of specific uncertainty. Within this thesis's scope, equal probabilities are defined for each state of the world since it was assumed each state of the world would have a similar likelihood to become a reality. The probability assignment of stochastic programming can also be further developed. Historical data might be assessed, or additional literature reviews can be carried out to develop enhanced distribution.

The **decomposition analysis** was applied to identify the role of air pollution control and macro-economic feedbacks through the decarbonization of the energy system in the EU [113]. Since the decomposition analysis can differ as seen with the transport sector, an analysis at the sectoral as well as at the Member State level can bring further understanding to the drivers of decarbonization in the energy system in a more disaggregated approach. A similar approach might also be followed to define the biomass potential, which can help determine the biomass utilization strategy during the energy transition. Further disaggregation of emission sources may convey a different structure to the effort sharing to reduce GHG emissions between sectors and the Member States, which can also be investigated in additional research.

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APPENDIX A

Appendix A 1: Electricity production comparison in 2015 in Croatia – Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (TWh)	TIMES PanEU (TWh)	Error Margin (%)
Coal	2.09	2.38	14%
Gas	1.18	1.17	1%
Geothermal	0.00	0.00	0%
Hydro	6.36	6.39	1%
Lignite	0.01	0.00	0%
Nuclear energy	0.00	0.00	0%
Pumped Hydro	0.17	0.15	11%
Solar	0.06	0.06	0%
Wind	0.79	0.83	5%
Biomass-waste	0.25	0.27	8%

Appendix A 2: Electricity production comparison in 2015 in Hungary – Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (TWh)	TIMES PanEU (TWh)	Error Margin (%)
Coal	0.07	0.06	14%
Gas	5.11	5.53	8%
Geothermal	0.00	0.00	0%
Hydro	0.23	0.23	0%
Lignite	5.20	5.90	13%
Nuclear energy	14.96	14.54	2%
Pumped Hydro	0.00	0.00	0%
Solar	0.12	0.11	8%
Wind	0.67	0.59	12%
Biomass-waste	2.14	1.91	10%

Appendix A 3: Electricity import trade Comparison in 2015 in Finland Import – Statistics vs. TIMES PanEU

Import (TWh)	ENTSO-E	TIMES PanEU	Error Margin (%)
Norway	0.147	0.147	0%
Russia	3.903	3.920	1%
Estonia	0.0245	0.027	10%
Sweden	18.664	18.350	2%

Appendix A 4: Electricity import trade Comparison in 2015 in Latvia Import – Statistics vs. TIMES PanEU

Import (TWh)	ENTSO-E	TIMES PanEU	Error Margin (%)
Latvia	3.974	3.770	5%
Russia	3.243	3.145	3%
Poland	0	0	0%

Appendix A 5: Electricity production comparison in 2015 in Italy – Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (TWh)	TIMES PanEU (TWh)	Error Margin (%)
Coal	39.31	35.76	9%
Gas	111.93	109.36	2%
Geothermal	5.82	5.32	8.5%
Hydro	45.02	43.00	4.5%
Lignite	0.00	0.00	0%
Nuclear energy	0.00	0.00	0%
Oil	10.16	10.16	0%
Pumped Hydro	1.43	1.57	9.7%
Solar	22.59	22.22	2%
Wind	14.71	13.66	7%
Biomass-waste	20.30	21.86	8%

Appendix A 6: Electricity production comparison in 2015 in France – Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (TWh)	TIMES PanEU (TWh)	Error Margin (%)
Coal	8.88	8.19	8%
Gas	23.89	21.87	8%
Geothermal	0.00	0.00	0%
Hydro	53.78	51.70	4%
Lignite	0.00	0.00	0%
Nuclear energy	416.80	418.63	1%
Oil	1.09	1.24	12%
Pumped Hydro	4.90	5.28	7%
Solar	7.26	7.12	2%
Wind	21.25	23.35	9%
Biomass-waste	7.64	7.50	2%

Appendix A 7: Final energy consumption of commercial in 2015 in Spain – Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (TWh)	TIMES PanEU (TWh)	Error Margin (%)
Petroleum products	41.0	39.60	3.4%
Gas	106.6	104.0	2.4%
Renewable Energy	0.0	0.0	0%
Electricity	254.2	253.5	0.2%
Heat	0.0	0.0	0%

Appendix A 8: Final energy consumption of residential in 2015 in Greece– Statistics vs. TIMES PanEU

Energy Carrier	Eurostat (PJ)	TIMES PanEU (PJ)	Error Margin (%)
Petroleum products	60.8	58.4	3.9%
Gas	14.7	14.1	4.1%
Renewable Energy	42.4	39.5	6.8%
Electricity	62.6	65.1	3.9%
Heat	0.0	0.0	0%

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