Global potential for the transformation of thermal power plants to thermal storage power plants

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Stuttgart, 09.05.2023 Pai Liu

Acknowledgments

As time flies by, I can't help but reminisce on the past four years, which began in 2019 when I embarked on my doctoral research. Back then, I often doubted whether I would be able to graduate successfully and whether I was truly cut out for a career in research. However, without realizing it, four years have passed, and now as I sit down to write this doctoral thesis, I am overwhelmed with emotions. Throughout this journey, I have come to realize that I could not have achieved this smooth progress without the help and support of the following individuals. I would like to extend my heartfelt gratitude to them:

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Abstract

With the trend of energy technology development and the continuous promotion of related renewable energy policies from governments, the share of renewable energy for power generation is constantly increasing, leading to the second phase of the energy transition, which is the problem of residual loads that arise as a result. Thermal storage power plants, also known as TSPP, can solve the problem of future residual loads. On one hand, they can provide a flexible power supply, and on the other hand, their built-in Carnot battery effectively addresses the issues of charging and discharging power from and to the electricity grid. In addition, the reduced use of fossil fuels by TSPP aligns with the current energy conservation and carbon emission reduction policies. More importantly, TSPP can be transformed from conventional thermal power plants. This kind of transformation can significantly reduce the installation costs compared to completely deconstructing the old power plant and building a new one.

According to a reference scenario aiming at 100% renewable supply, Germany's residual load is projected to reach 213 TWh by 2040, which accounts for one-third of the total electricity generation at that time. To meet this demand, approximately 70 GW of TSPPs need to be transformed. The purpose of this dissertation is to investigate whether this TSPP transformation is feasible from a technical point of view. Using Germany as a case study, this dissertation assesses the feasibility of TSPP on a global scale to achieve the carbon reduction targets and the energy policies in different countries.

This thesis develops research from three aspects. Firstly, an analysis of the photovoltaic potential in Germany is performed using a Geographic Information System (GIS) as auxiliary software. Potential geographical locations suitable for installing photovoltaic systems across Germany are identified, and it is determined that the total area of these locations is sufficient to meet the 105 GW photovoltaic demand required for TSPP transformation according to the reference scenario. Furthermore, a classification of all traditional thermal power plants in Germany is conducted to prioritize the most suitable plants for transformation.

The second part analyzes the residual biomass potential in Germany. The total potential of the three main types of residual biomass is summarized, and an algorithm is developed to allocate the area for these biomass potentials as well as the area for photovoltaics in the transformed TSPPs.

In addition, this thesis provides a detailed comparison of the electricity generation costs for various types of thermal power plants before and after the transformation by making an economic analysis. The result of this cost comparison demonstrates that TSPP can effectively mitigate the large price fluctuations of fossil energy sources, and at the same time, they substantially reduce the cost of additional electricity generation which is related to less CO_2 emissions.

In conclusion, the final goal of this thesis is to present the potential of transforming conventional power plants into TSPPs in Germany in the form of an atlas. This includes a macro-level analysis of the transformation plan for a total of 70 GW capacity in Germany, along with the corresponding installation locations for photovoltaics and biomass. It also includes a micro-level analysis, focusing on optimal transforming plans for specific thermal power plants.

Zusammenfassung

Mit dem Trend der Entwicklung von Energietechnologien und der kontinuierlichen Förderung entsprechender erneuerbarer Energiepolitiken durch Regierungen steigt der Anteil erneuerbarer Energien für die Stromerzeugung an, was zur zweiten Phase der Energiewende führt, nämlich dem Problem der Residuallast, die sich daraus ergeben. Wärmespeicherkraftwerke, auch als WSK bekannt, können eine Lösung bieten, um das Problem der Residuallasten anzugehen. Einerseits sorgen sie für flexible Stromversorgung, und darüber hinaus löst ihre integrierte Carnot-Batterie effektiv das Problem der Lade- und Entladeleistung von und zum Stromnetz. Andererseits entspricht die Reduzierung des Einsatzes von fossilen Brennstoffen durch WSK den aktuellen Energieeinsparung und Kohlenstoff-Emission Reduktion. Was noch vorteilhafter ist, WSK kann von herkömmlichen thermischen Kraftwerken umgewandelt werden, was die mit der Transformation verbundenen Baukosten erheblich reduzieren kann.

Gemäß dem Referenzszenario wird erwartet, die auf eine 100%ige Versorgung aus erneuerbaren Energien abzielt, dass die Restlasten in Deutschland bis 2040 213 TWh erreichen, was einem Drittel der Gesamtstromerzeugung zu diesem Zeitpunkt entspricht. Um diesen Bedarf zu decken, müssen etwa 70 GW WSK umgewandelt werden. Das Ziel dieser Dissertation ist es, diese WSK -Umwandlung aus technischer Sicht zu analysieren, Deutschland als Fallstudie zu verwenden, ihre Machbarkeit weltweit zu bewerten und die Strategien zur Erreichung dieses Ziels zu untersuchen.

Diese Dissertation untersucht das Thema aus drei Aspekten. Erstens wird eine Analyse des Photovoltaik-Potenzials in Deutschland mit Hilfe von Geografisches Informationssystem (GIS) als Hilfssoftware durchgeführt. Potenzielle geografische Standorte, die sich für die Installation von Photovoltaiksystemen in ganz Deutschland eignen, werden identifiziert, und es wird festgestellt, dass die Gesamtfläche dieser Standorte ausreicht, um den Photovoltaikbedarf von 105 GW für die WSK - Umwandlung zu decken gemäß dem Referenzszenario. Darüber hinaus wird eine Klassifizierung aller herkömmlichen thermischen Kraftwerke in Deutschland durchgeführt, um die am besten geeigneten Kraftwerke für die Umrüstung zu priorisieren.

Der zweite Teil konzentriert sich auf die Analyse des Restbiomasse-Potenzials in Deutschland. Das Gesamtpotenzial der drei Hauptarten von Restbiomasse wird

zusammengefasst, und ein Algorithmus wird entwickelt, um die Fläche für dieses Biomasse-Potenzial sowie die Fläche für die Photovoltaik in den umgewandelten WSK zuzuweisen.

Darüber hinaus liefert diese Dissertation eine detaillierte Berechnung der Stromerzeugungskosten vor und nach der Umwandlung für verschiedene Typen von Kraftwerken aus wirtschaftlicher Sicht. Die Ergebnisse zeigen, dass WSK-Preisfluktuationen aufgrund verschiedener Faktoren bei fossilen Energiequellen effektiv entgegenwirken können. Darüber hinaus reduzieren sie die zusätzlichen Stromerzeugungskosten erheblich, die durch die Emissionen von Kohlendioxid entstehen.

Zusammenfassend präsentiert diese Dissertation das Potenzial der Umwandlung konventioneller Kraftwerke zu WSK in Deutschland in Form eines Atlas. Dies umfasst eine makroebene Analyse des Umwandlungsplans für insgesamt 70 GW Kapazität in Deutschland sowie die entsprechenden Installationsstandorte für Photovoltaik und Biomasse. Es umfasst auch eine mikroebene Analyse, die sich auf den optimalen Umwandlungsplan für ein bestimmtes thermisches Kraftwerk konzentriert.

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1. Introduction

With the continuous advancement of energy transition in different countries, the proportion of installed capacity of variable renewable energy (VRE) is continuously increasing [1]. As a result, the upcoming residual loads will pose a significant negative impact on the stability of power supply [2]. TSPP, on the other hand, is an excellent solution specifically designed to provide flexible and stable power supplies to the residual loads. Based on the established TSPP configuration and future energy scenario, this thesis gives solution of transforming the traditional conventional power plants to TSPP by analyzing and distributing PV and biomass resources for these power plants, using geographical analysis to demonstrate the practical feasibility of this transformation from a real-world perspective. Finally, a comprehensive global atlas of the TSPP transformation solution is obtained. Germany, in this thesis, is as a first example for the global TSPP Atlas.

1.1 Motivation

Before the concept of energy transition was introduced, power generation in various countries around the world in the previous century mainly relied on fossil fuels and nuclear energy. Power plants utilizing conventional fossil fuels could operate throughout the year without frequent interruptions, providing reliable and stable power supply. Moreover, these conventional power generation methods were economically efficient. On the other hand, emerging renewable energy technologies such as photovoltaics during that time had limitations in terms of efficiency, and they were prohibitively expensive, preventing them from becoming mainstream sources of power generation [3].

However, in the 21st century, with globalization and the industrialization of countries worldwide, the total electricity generation has been constantly increasing, leading to a growing demand for fossil fuels [4]. This has resulted in two outcomes:

1) Economic and political influence resulting in increasing fuel prices and big fluctuations: Figure 1 describes the price changes of fossil fuels over the past few years [5][6].From this graph, it is evident that, from a long-term perspective, fossil energy prices have been slowly rising in tandem with the increasing trend of human industrial activities. It is worth noting that this uprising trend is not specific to any country or region. For instance, in Germany, where population changes and

variations in annual electricity consumption are expected to be relatively stable in the foreseeable future, the prices may not exhibit significant fluctuations [7][8]. However, as the global population continues to grow, the prices of energy resources are expected to steadily rise. This upward trend will gradually increase the generation costs of conventional power plants. From a short-term perspective, it can be observed that fossil energy sources, particularly natural gas, are susceptible to significant price fluctuations influenced by various factors, such as policies and temporary production cuts. These fluctuations impose a significant burden on the cost of traditional power generation.

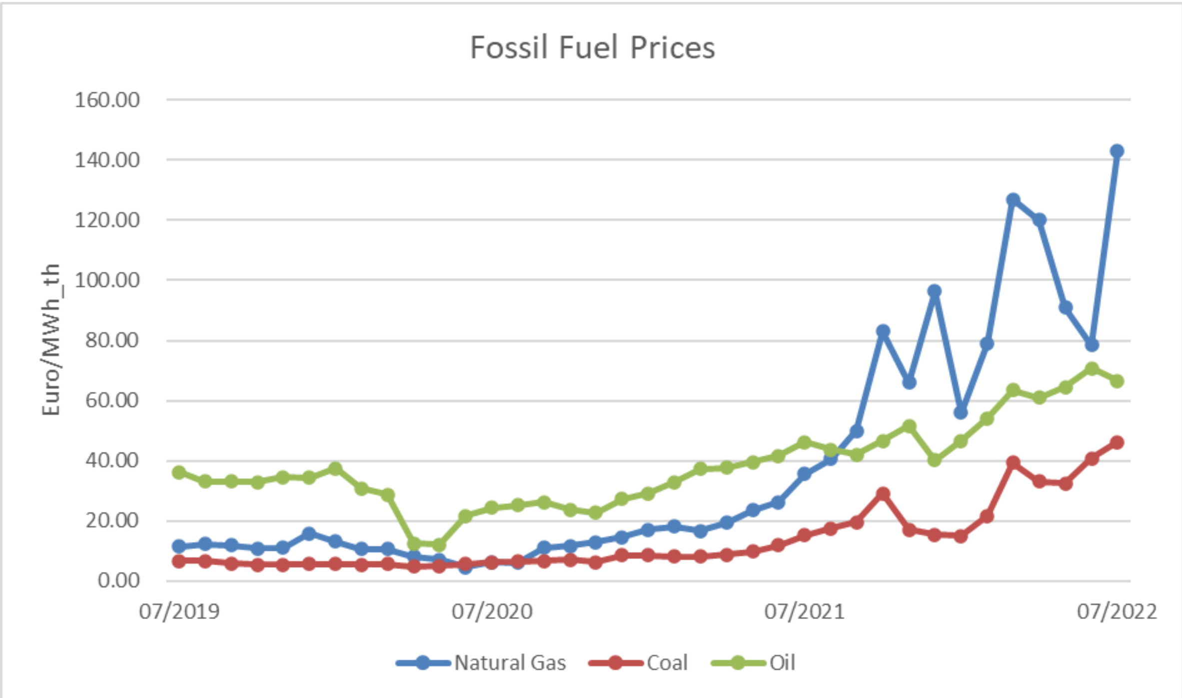

Figure 1: Fossil fuel prices in the past 3 years (Euro per MWh_{th}) [5][6]

2) The implementation of carbon-emission reduction policies and the introduction of carbon trading system: Due to the constant frequencies in extreme weather conditions in recent years and the increasing awareness of environmental protection, several countries have incorporated carbon emission reduction in their policymaking. Carbon trading is one measure to reduce carbon emissions. Figure 2 illustrates the price trend of carbon trading in the European Union since 2008 [9][10]. From this trend, it can be observed that the price of carbon trading has been increasing year by year, and with the continuous implementation of policies

[11][12], this price is expected to continue rising in the foreseeable future. This will further burden the generation costs of fossil power plants, while renewable energy sources do not require additional costs in this aspect.

Figure 2: EU Carbon trading price history data from EU-ETS

While the generation costs of conventional power plants continue to rise, there has been a significant decrease in the cost of renewable energy sources, primarily led by photovoltaics due to technological advancements during these decades [3]. As a result, fossil energy sources no longer possess a definitive price advantage over renewable energy sources in terms of power generation costs. This further accelerates the pace of energy transition. Currently, the energy transition in different countries can be roughly divided into two phases based on time:

The first phase involves the construction of variable renewable energy power plants primarily based on wind, solar, and hydro energy through policy interventions. During this stage, the proportion of power generation from traditional fossil fuels is gradually reduced. Some countries may even phase out coal-fired and nuclear power plants in advance in order to achieve decarbonization goals [1]. For instance, according to Germany's energy policy, the government aims to progressively decommission conventional power plants like lignite- and coal-fired power plants and phase them out entirely by 2040, along with a gradual phase-out of lignite and coal, and a transition to renewable energy sources [1]. Building on this, AURORA has conducted a forecast of Germany's power generation structure in 2020, as depicted in Table 1, which presents the projected installed capacities for Germany in 2040 based on current policies and trends[13]. It can be observed from the table that the major contributors to Germany's future power generation will be photovoltaic and wind energy, while energy storage systems are primarily based on batteries.

Table 1: Forecasted installed energy capacity in Germany in 2040 [13]

Power plant type	***[GW]***
Solar	119.9
Onshore wind	70.7
Offshore wind	30
Open Cycle Gas Turbine	26.9
CCGT	19.8
Battery storage	11
Pumped storage	6.2
Oil	5.4
Other baseload	4.9
Hydro	4.1
Biomass	3.4
DSR	2.1
Other renewables	0.5

When the proportion of electricity generation from variable renewable energy reaches a certain level and conventional power plants that previously provided the base load are shut down, a new issue gradually emerges, which is the integration of the residual loads. Figure 3 and Figure 4 show 2 different situations where residual loads negatively affect the stability of the grid [14].

Figure 3 illustrates a time series of energy demand and supply in Germany from Jan. 29th to Feb. 4th according to the energy structure from AURORA [13]. From this graph, we can observe that during this period, when solar and wind energy are unable to provide sufficient power due to weather conditions, energy discharge from energy storages like pump storages and battery storages becomes necessary. However, due to insufficient electricity generation from photovoltaic and wind sources during this period, the energy storage devices cannot be charged daily at all. As a result, all energy storage systems become ineffective, and the energy supply relies on importing electricity from abroad to maintain the energy demand. Also, Germany's total pump storage capacity is only about 6.2 GW, and it is challenging for this number to significantly increase in the future. Therefore, the electricity shortfall during this period can only be met through electricity imports.

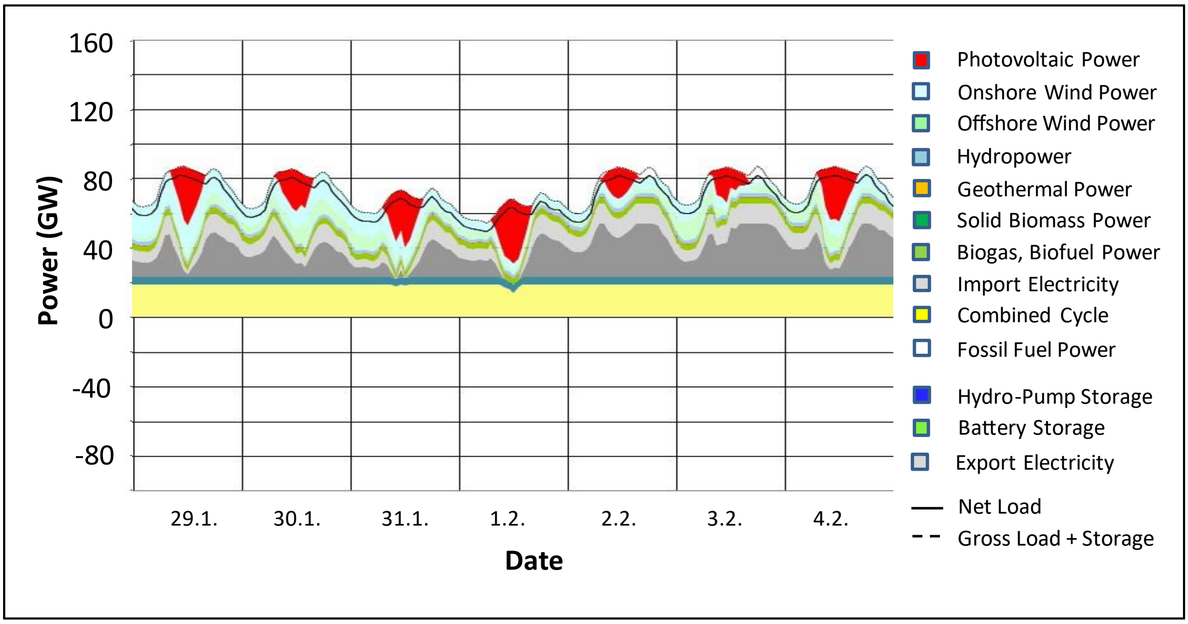

Figure 3: Time series of all kinds of power generation from 29.1 to 4.2 [14].

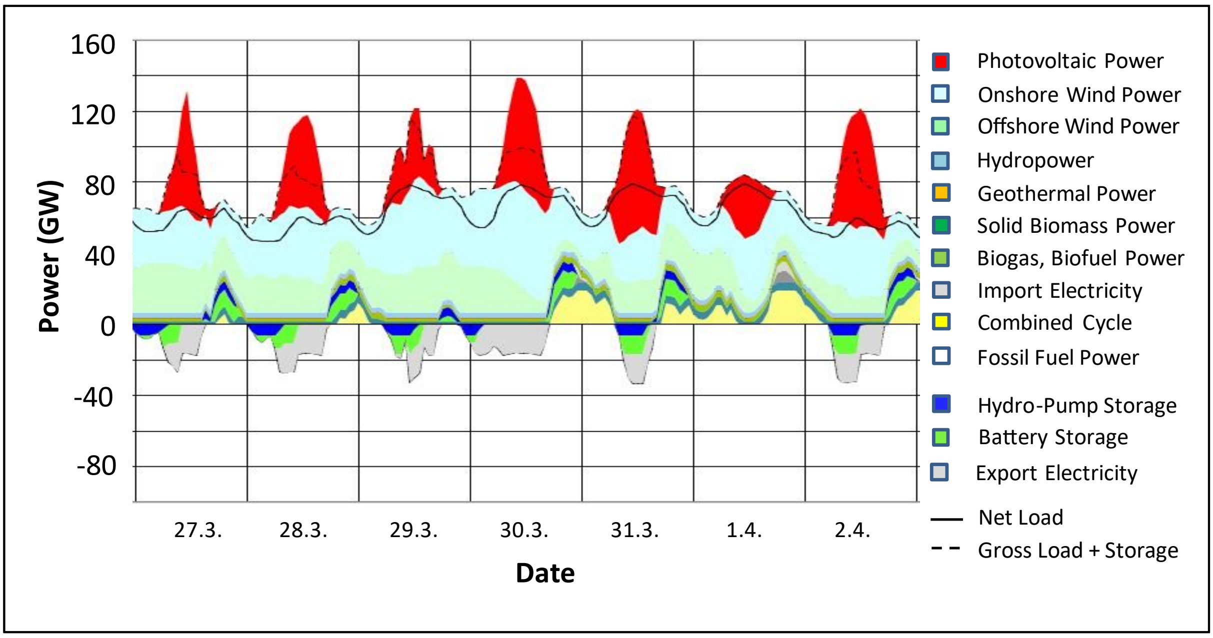

Figure 4: Time series of all kinds of power generation from 27.3 to 2.4 [14].

Figure 4 presents a completely opposite situation. From Mar. 27th to Apr. 2nd, the conditions for solar and wind electricity generation are highly favorable, resulting in a grid surplus of electricity compared to the energy demand during that time. While there is a desire to store this excess electricity using pump storage and battery storage, the limitations of installed capacity prevent the complete storage of this surplus power. Consequently, this excess electricity can only be wasted or exported to other countries. Such situations occur frequently throughout the year.

From this point on, the second phase of energy transition has been entered, which involves finding solutions to address the supply inadequacies and gird surplus caused by residual loads. The objective is to meet the goals of reducing carbon emissions while ensuring a reliable and flexible electricity supply. A typical solution is to increase the installed capacity of energy storage systems in the grid, consists of pumped hydro energy storage [15], stationary battery storage system [16], or power to gas technology[17], etc. The electricity surplus from variable renewable power plants (such as wind and PV) can either be imported(exported) from(to) the foreign countries thanks to the balancing mechanisms in the European electricity network, or be stored in these energy storage systems. Another alternative from the perspective of the supplier side is to incorporate other renewable energy sources such as geothermal power plants.

However, this approach on hand discussed in this thesis combines self-power generation, energy storage capabilities, and reducing power generation costs, which is known as thermal storage power plants (TSPP).

A TSPP power plant that would be able to flexibly cover the residual load should have the following capabilities:

- Absorb power surplus.
- Standby operation during times with enough variable renewable supply
- Fast transition from standby to flexible residual load supply when needed.
- Base load supply for up to some days or weeks
- Peak load supply for some hours or less.
- All functions of a TSPP should be based preferably on renewable primary energy sources like biomass and PV

This PhD research work focuses primarily on finding ways to preserve conventional power plant components by transforming them into TSPPs that primarily utilize photovoltaic and bioenergy as their main energy sources.

1.2 Design of a basic thermal storage power plant (TSPP)

A TSPP consists mainly of the following components:

- Photovoltaic panels: One primary energy source is a large-scale solar PV array that can directly supply electricity to the grid. Excess energy can be transformed to heat in order to charge the thermal storage system.
- Thermal Storage System (TES), also known as Carnot Battery: This module includes electric heaters, thermal storage tanks, and a steam turbine for electricity generation. It stores excess power from the grid and from the solar PV array in form of thermal energy for later use.
- Backup biomass boiler: This component serves as a backup power source and primarily burns biomass such as bio coal as the main fuel for combustion. It provides primary energy when there is insufficient solar energy to power the steam turbine.
- Gas turbine consuming natural gas: This component is used to supply power during peak load demand. It operates on natural gas (or in the long-term biomethane) and provides additional power support when required.

Figure 5 shows a basic schematic of a TSPP. As shown in Figure 5, two similar TSPP configurations are presented. The top figure depicts the TSPP configuration that was initially considered at the beginning of my doctoral project. It can be seen that the heat released from the boiler and the waste heat from the gas turbine are stored in the thermal storage tank. The advantage of this configuration is that the power plant's operational mode is more flexible, and the thermal energy in the storage tank can be charged at any time. However, from a practical perspective, this configuration is not as easily achievable. Therefore, shortly afterward, the TSPP configuration was updated. As illustrated in the bottom figure, the thermal energy is ultimately used to power the steam turbine rather than being stored in the thermal storage tank. While this configuration sacrifices some flexibility, it can be immediately applied in real-world projects. As a result, this configuration was adopted as the final TSPP configuration.

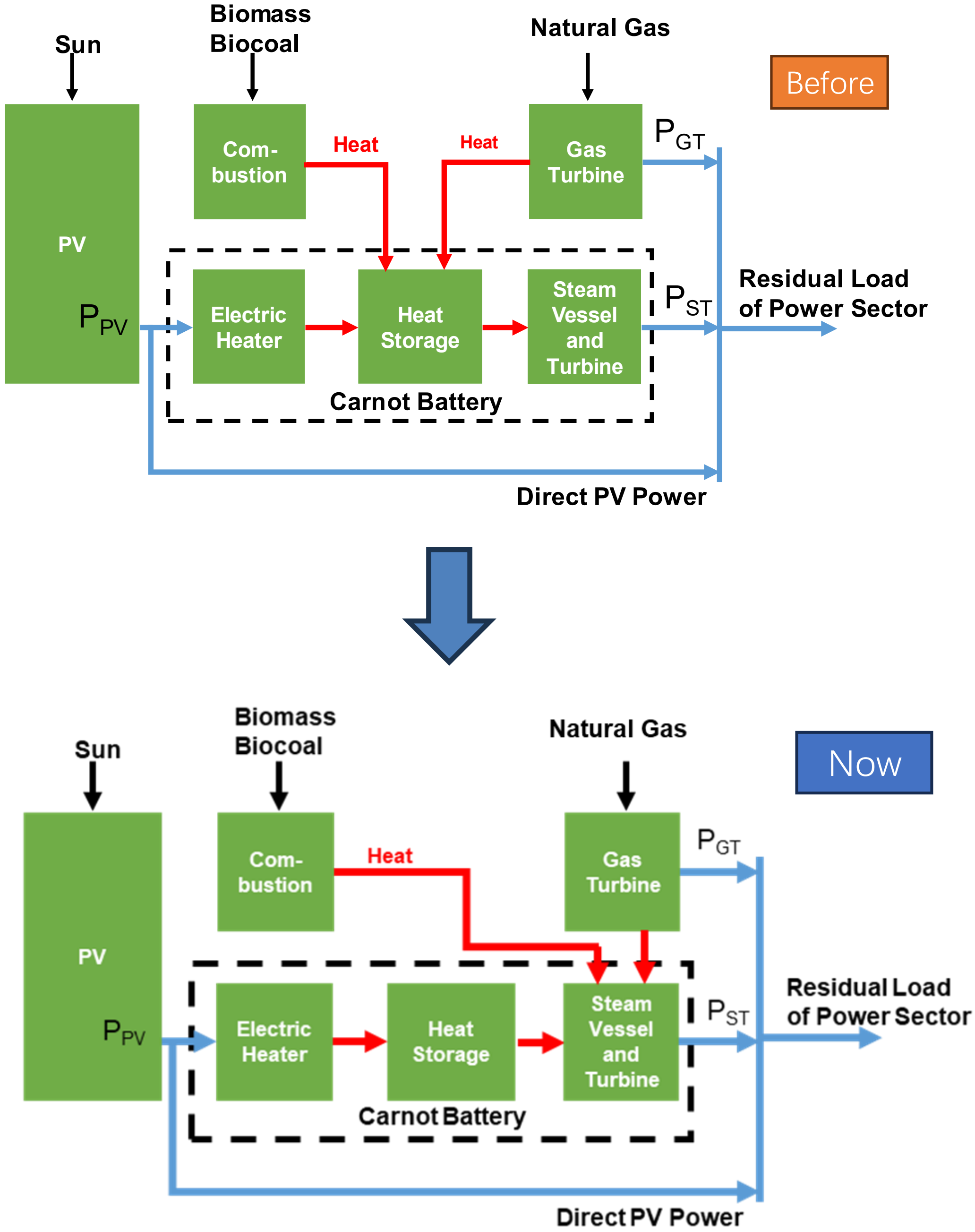

Figure 5: Simplified schematic of a TSPP. Top: Old configuration. Bottom: Configuration applicated now and in this thesis

1.3 Operating conditions of TSPP

The operation condition of a TSPP is influenced by various factors, including real-time electricity demand from the grid, PV generation conditions, and the state of charge of the Carnot battery. Based on different supply-demand conditions, TSPP generally have the following operation modes [18]:

1) Firstly, under good solar conditions where the electricity generated by PV exceeds the real-time demand from the grid, PV will directly supply electricity to the grid. In this situation, TSPP operates at its highest efficiency. Additionally, the surplus electricity from PV will be used to charge the Carnot battery through electric heaters within the TSPP. When surplus occurs on the grid, the excess electricity from the grid can also be used to charge the thermal storage tanks.

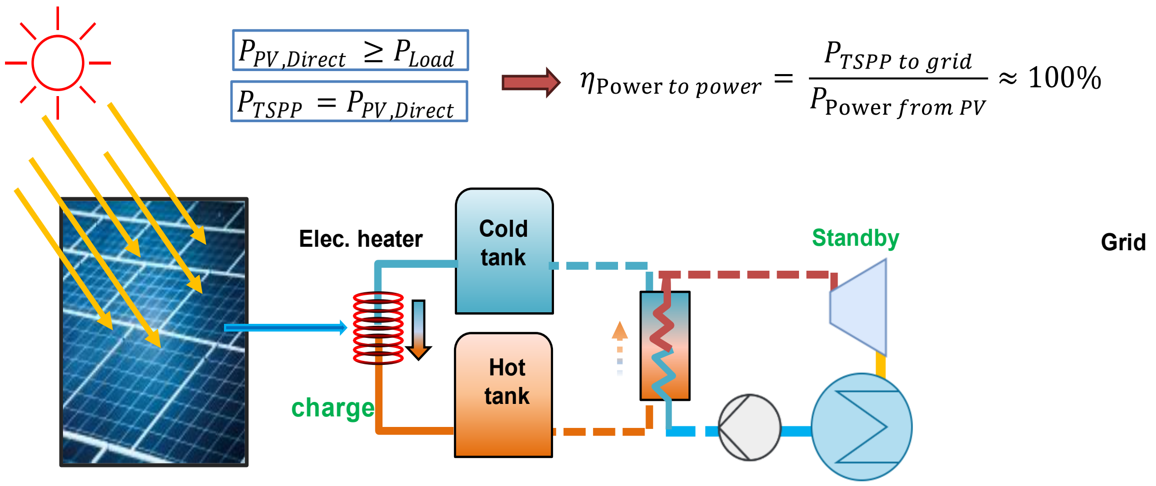

Figure 6: Operation mode of TSPP (Direct supply+ TES charging)

2) When the supply of electricity from PV is insufficient to meet the demand of the grid or when there is a deficit in grid supply during certain periods at night, the steam turbine of TSPP will be activated. The thermal storage will release heat, which will be converted into electricity through the steam turbine. The thermal storage tanks, when fully charged, can provide heat to the steam turbine for full-power electricity generation for approximately 12 hours. When the stored heat is insufficient, the boiler, serving as a backup heat source, will be utilized, and biomass or bio-coal will be combusted to generate enough heat to the steam turbine.

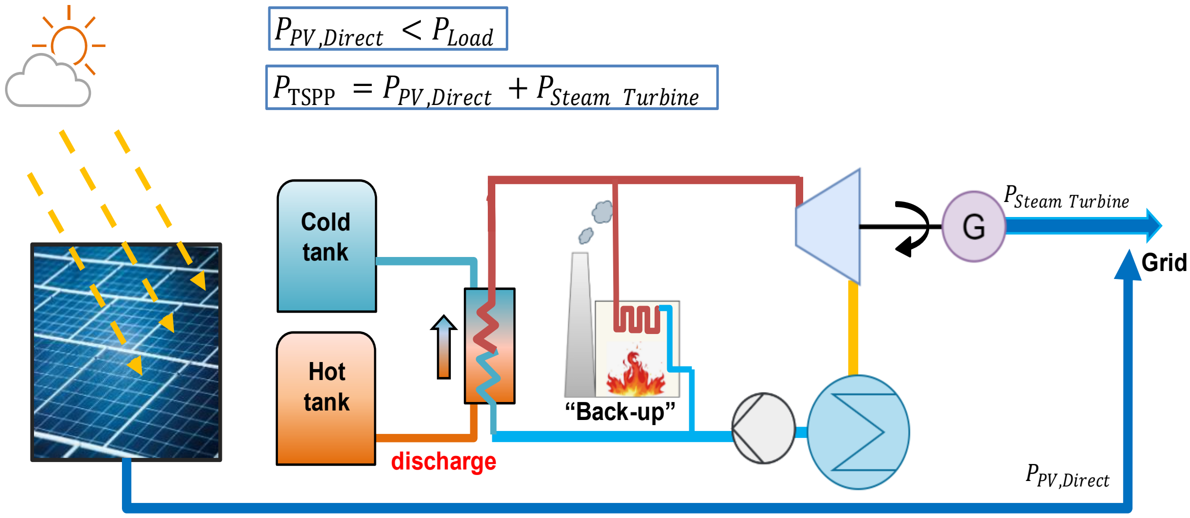

Figure 7: Operation mode of TSPP (PV + TES discharging with backup boiler)

3) The third operation mode represents the most extreme case: when the deficit in electricity on the demand side is so large that the combined output power of PV and the steam turbine is insufficient to meet the demand, the gas turbine will be finally activated. It utilizes the combustion of natural gas to generate additional electricity to compensate for the peak load from the demand side. Furthermore, the waste heat discharged from the gas turbine can be partially utilized to provide heat to the steam turbine or charge the Carnot battery.

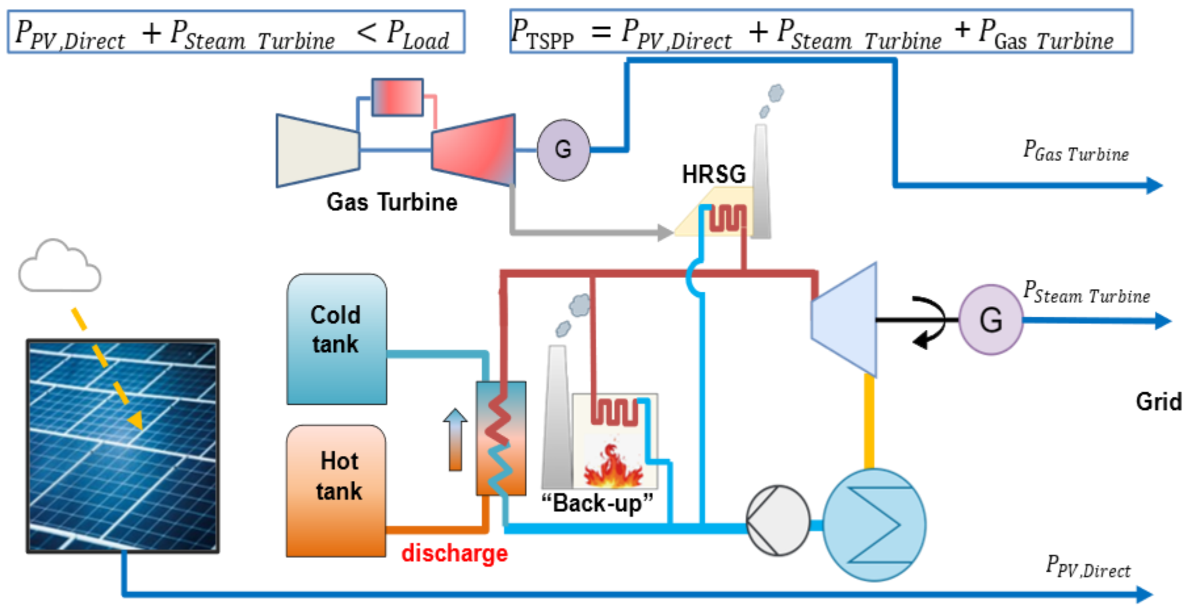

Figure 8: Operation mode of TSPP (PV + Steam turbine + Gas turbine)

1.4 Major goals and the structure of the thesis

The main objective of this paper is to validate the feasibility of this approach on a global scale, based on the existing TSPP configuration, through a practical perspective using Geographic Information Systems (GIS). The approach is to find solutions for transforming conventional thermal power plants to thermal storage power plants in a certain country. The final result should be an atlas collection that includes a complete transforming plan, incorporating the transformed TSPP locations and the analysis of each power plant. Specifically, this result should address the following main issues:

About power plants:

- Which types of conventional power plants fall within the scope of transformation?
- Where are these power plants located?
- Where can the relevant information about these conventional power plants be obtained?

About PV/biomass potential:

- What is the total potential of PV and biomass?
- Where are the locations of the PV installation and biomass resources?

About TSPP transformation:

- How much does TSPP cost when generating electricity after transformation?
- How to distribute the PV/ biomass areas to the TSPP?

This dissertation is composed of the following sections: Firstly, the first chapter provides an introduction to the background of global energy transition, the composition of TSPP and its various operational modes, as well as the final purpose and objectives of this study. The second chapter provides a brief overview of the entire research framework for TSPP, the current research progress achieved so far, and the specific position or role of my research within the overall TSPP research package. Chapter 3 presents a detailed discussion on the preliminary preparations required to accomplish TSPP-GIS, including analyzing the photovoltaic and bioenergy potentials of a particular country. Additionally, GIS analysis is required to determine the specific locations and distribution of these potentials, as well as how to allocate the optimal PV locations and bioenergy resources for each TSPP. Finally, the fourth section shows partial results of

TSPP-GIS and provides a brief discussion on potential future analyses and conclusions.

2. State of research

2.1 Determination and simulation of transformation pathways

The energy transition of TSPP implementation in a specific country can generally be divided into two sides:

Firstly, from the demand side, it is necessary to calculate the total amount of the residual load profile in the country for the coming decades. Secondly, from the supply side, one aspect involves designing TSPP specifications that can meet the requirements of the residual load profile based on the specific conditions of the country. This includes determining the total capacity and configuration of the TSPP to ensure reliable and efficient power supply. Another aspect from the supply side is to analyze the bioenergy and photovoltaic potentials that can support the TSPP in the country. This entails assessing the availability and feasibility of utilizing bioenergy resources, such as biomass or biogas, and evaluating the solar potential for PV installations.

In more detail, the entire process or research structure of assessing the potential for TSPP transition in a certain country, as summarized in Figure 9, can be described as follows.

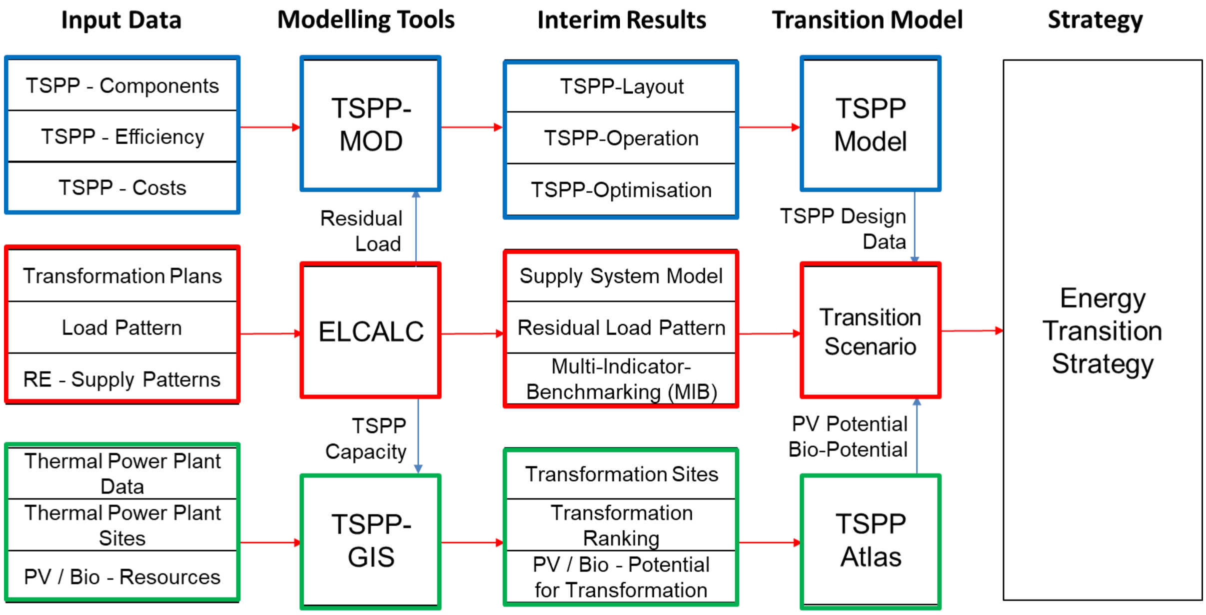

Figure 9: The whole package of TSPP transformation solution [19]

The first step is to collect relevant power generation time series for the country, such as the annual electricity load curve and the generation curves for all relevant renewable energy sources, such as PV, wind energy, hydroelectric power, etc. Additionally, the actual situation and energy policies of the country need to be considered to determine the future energy structure and the electricity demand trends for the next few decades. For example, in the case of Germany mentioned in this thesis, the future German electricity demand is expected to remain stable or slightly decrease over the next decades, while the percentage of renewable energy is projected to continuously increase based on the energy policies implemented [1][4][14].

After collecting the information mentioned above, it will be imported into an analysis software called ELCALC. Developed by Franz Trieb, this simulation software is used in this step to determine the total amount of residual load in Germany in the year 2040 before the TSPP transformation, as well as the total capacity required to transform the conventional power plants to TSPP to supply electricity for this residual load[18].

After obtaining the residual load time series for Germany, the next step is to use another tool called WSK-MOD to determine the corresponding specifications and the equipment for the TSPP. This tool allows for the flexible adjustment of layout and efficiency of each TSPP component, as well as its share in energy production. Through iterative adjustments, the tool ultimately determines the most suitable TSPP configuration for Germany, including the specific sizes of its components. With this tool, the total capacity of the TSPP, as well as the capacity of the steam turbine and gas turbine within the TSPP can also be determined [18].

With the corresponding specifications for the TSPP in hand, the next step is to use the ELCALC tool to conduct the simulation once again. However, this time the analysis includes the transformed TSPP to determine whether the residual load in Germany can be fully covered by the TSPP after the transformation. During this process, the scenario will be continuously fine-tuned. ELCALC incorporates a benchmarking system that evaluates each scenario based on a series of indicators of sustainability, including carbon emissions, land occupancy, and other factors. Finally, a TSPP transition strategy that best aligns with the requirements of Germany will be developed.

The aforementioned steps and research achievements regarding ELCALC represent the latest progress made by my colleague Franz Trieb and other members of TSPP working group before the start of my PhD research. Through these steps, a comprehensive TSPP transformation scenario tailored to Germany can be developed, including the total power of the transformed TSPP, sizes of its components, their efficiencies, and the required amounts of different energy sources such as biomass, PV, and natural gas. My PhD research focuses on the portion highlighted in the green box in Figure 9, which pertains to addressing the geographical aspects of these power plants' energy sources, including the installation locations of PV panels and the distribution of domestic biomass resources, etc. I also participated marginally in the elaboration, testing and application of TSPP-MOD as documented in [18].

The final outcome will be a compilation of an atlas for the TSPP transformation in Germany, including the geographical locations of each TSPP, their ranking for the transformation, as well as the installation locations of their PV panels and the sources of biomass after the transformation. All the achievements will be integrated into a GIS software called TSPP-GIS. Ultimately, the complete TSPP transformation plan consists of TSPP-GIS, TSPP-MOD, and ELCALC in order to produce all information related to a scenario for energy transformation in the power sector of Germany [20].

2.2 Definition and quantity structure of the target scenario

According to the paper from Trieb and Thess, a scenario about German TSPP transformation was carried out in 2020 based on the country's energy policies [20]. Table 2 presents the power capacity and the estimated annual electricity generation for each kind of power plant according to this scenario. Based on their analysis, conventional power plants, such as coal-fired power plants and nuclear power plants will be fully deactivated in 20 years, and at the same time, the PV capacity will be expanded to about 135 GW, which result in the consequence that the total electricity demand from German residual load in 2040 will be approximately 213 GWh. To meet this demand, around 70 GW of TSPP capacity is required to be newly built or transformed from conventional power plants, including 21 GW from steam turbines and 49 GW from gas turbines. Additionally, considering Germany's solar radiation conditions, approximately 105 GW of new photovoltaic plants is needed to provide energy for the TSPP [20].

Meanwhile, the energy sources for different components of TSPP are not the same. According to the plan, the steam turbines are primarily fueled by Carnot batteries, and the backup heat source is provided by bioenergy. The bioenergy sources mainly include crop residues from farmlands, residual wood from forests, and organic waste such as biomass in urban areas. Energy crops such as corn are not discussed in this paper, as the goal of TSPP's energy transition is to utilize residual biomass as much as possible without occupying limited agricultural land. The energy for gas turbines primarily comes from natural gas, that in the long-term could be substituted by biomethane. Currently, the efficiency of converting bioenergy to biomethane is approximately 60%, with the potential to reach 65% in the future [19]. The ideal TSPP model in the future would rely on roughly 35% solar energy through direct use and storage and 65% bioenergy as a backup primary energy source, but this paper still includes the utilization of natural gas.

A detailed description of this scenario can be found in [20]

Table 2: Energy scenario with TSPP of this thesis according to [20]

Model Year	*2020*	*2030*	*2040*
Renewable Capacity (MW)			
Photovoltaic	48500	105000	135000
Wind Onshore	56500	70000	75000
Wind Offshore	8400	12500	14000
Hydropower	5700	5640	5640
Solid Biomass, Wood, Waste	3000	1800	0
Biogas, Energy Crops	4700	0	0
Geothermal Power	38	250	1000
Hydropower Imports	0	250	1000
Thermal Storage Power Plant Capacity (MW)			
TSPP Photovoltaic	0	52500	105000
TSPP Steam Turbines	0	10500	21000
TSPP Gas Turbines	0	24500	49000
Fossil Power Capacity (MW)			
Gas Turbines	1390	17200	19300
Hard Coal Power Plants	22000	14500	0
Combined Cycles and Combined Heat and Power	28700	15500	0
Other	5700	0	0
Nuclear Plants	9400	0	0
Lignite Plants	21200	7000	0
Storage and Grid Capacity (MW)			
Pump Storage	9850	9850	9850
Net Transfer Capacity Import	27000	27000	27000
Net Transfer Capacity Export	23000	23000	23000

2.3 Simulation Results according to ELCALC and TSPP-MOD

Once the TSPP transformation scenario was determined, the next step was to import 70 GW of TSPP into ELCALC to confirm that they covered the German residual loads well. Figure 10 displays the electricity load time series in Germany during the same date range as in Figure 3, considering the presence of TSPP [14][20]. From this graph, it can be observed that the TSPP perfectly showcases the different operational states mentioned above. During the period from Jan. 29th to Feb. 2nd, the solar photovoltaic generation is insufficient to produce surplus energy for storage. As a consequence, stored heat in the thermal storage system is depleted. At this time, biomass boiler and the gas turbine together with its Heat Recovery Steam Generator (HRSG) act as backup energy sources to compensate for the shortfall in electricity generation, which is very flexible and reliable.

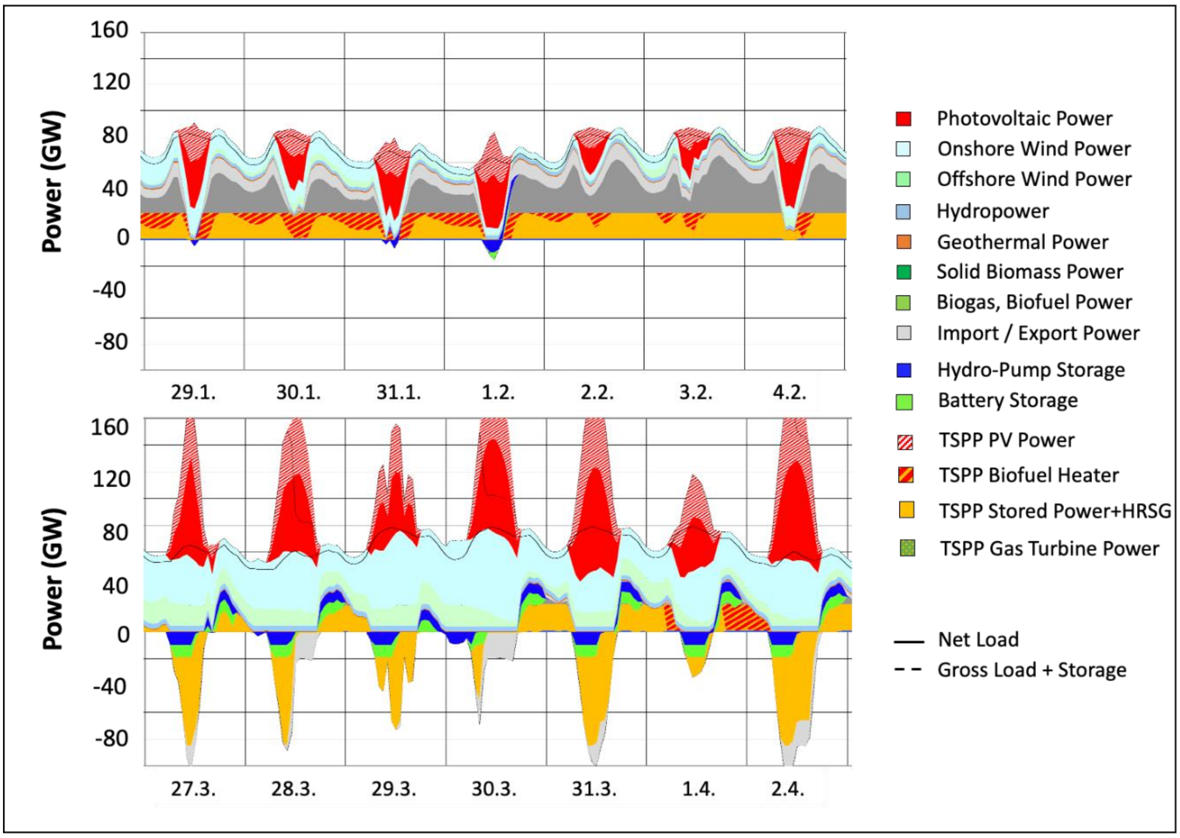

Figure 10: Time series of German power generation with TSPP in 2040 [14][20]

During the period from Mar. 27th to April 2nd, there is ample sunlight and wind power, generating sufficient electricity to satisfy demand. With the presence of the TSPP, the surplus electricity generated is used to charge the thermal storage. When it comes to nighttime, the thermal storage system releases heat to operate the steam turbine. Due to the continuous availability of wind energy, the peaking gas turbines as well as the HRSG are idle in this period. On the evening of April 1st, while the thermal storage capacity is insufficient, the biomass boiler provides the extra necessary heat for the steam turbine.

3. Cumulative part of the dissertation

This thesis is based on the work published/ submitted in the following journal contributions:

I. Assessment of power plant sites and potential PV areas

Pai Liu, Franz Trieb, Transformation of the electricity sector with thermal storage power plants and PV – a first conceptual approach, *Journal of Energy Storage* 44 (Part B) (15 December 2021), 103444, https://doi.org/10.1016/j.est.2021.103444.

II. Cost comparison of conventional power plants and TSPP

Pai Liu, Franz Trieb, Cost comparison of thermal storage power plants and conventional power plants for flexible residual load coverage, *Journal of Energy Storage*, Volume 56, 2022, https://doi.org/10.1016/j.est.2022.106027

III. Assessment of PV and biomass areas (New approach) and establishment of TSPP-Atlas

Pai Liu, Franz Trieb, German Atlas of Thermal Storage Power Plants (TSPP) – A First Approach -, *Journal of Energy Storage*, Volume 72, Part D, 2023,

https://doi.org/10.1016/j.est.2023.108603

Also, further research progress regarding TSPP presented in this dissertation have been published/ submitted in the following journal contributions:

- Franz Trieb, Pai Liu, Gerrit Koll, Thermal Storage Power Plants (TSPP) - Operation modes for flexible renewable power supply, *Journal of energy Storage*, https://doi.org/10.1016/j.est.2022.104282.

- Franz Trieb, Judith Jäger, Michael Geyer, Gerrit Koll, Pai Liu, Thermal Storage Power Plants – Key for transition to 100% renewable energy, *Journal of Energy Storage*, https://doi.org/10.1016/j.est.2023.109275.

Paper I: Assessment of PV Atlas in Germany

Pai Liu, Franz Trieb, Transformation of the electricity sector with thermal storage power plants and PV – a first conceptual approach, Journal of Energy Storage 44 (Part B) (15 December 2021), 103444, https://doi.org/10.1016/j.est.2021.103444.

The contribution of this paper is described as follows:

Pai Liu: Methodology, Software, Formal analysis, Writing – original draft

Franz Trieb: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Transformation of the electricity sector with thermal storage power plants and PV – A first conceptual approach

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ABSTRACT

The paper presents a model algorithm for a global transformation of conventional thermal power plants to thermal storage power plants (TSPP). TSPP are thermal power stations that provide highly flexible and at the same time renewable power. The idea behind such transformation is to conserve the firm capacity of the existing thermal power plant fleet and at the same time substitute the related fuel demand by solar energy. Taking Germany as a reference case, several ranking criteria were applied to existing power stations in order to identify a priority list for such transformation. In order to relate the available solar energy potential to each power plant of this list, a geographic information system was set up in order to quantify and identify suitable land area for potential PV installations nearby the plants. After briefly recapitulating the potential function and impact of TSPP in the German national power supply system, the paper proposes a method of ranking existing thermal power plants and of identifying the required PV potential for their transformation. The preliminary results show the feasibility of such approach, identify several limitations and provide first ideas for further development.

1. Introduction

A key challenge of transforming the power sector from fossil-fuel-based to renewable-energy-based generation is the residual load curve. Expanding renewables causes several disruptive impacts on operation of conventional thermal power plants, like strong variability and reduced capacity factors that lead to reduced economic turnover and higher production cost. In the future, fossil-thermal power plants will either be shut down or transformed to use renewable instead of fossil primary energy sources. In the long-term, the residual load must also be covered by renewable energy, further reducing perspectives for conventional power plants.

Energy storage is a way to smoothen the variability of power supply caused by renewable energy sources (such as windless or cloudy weather). Nowadays several types of energy storage are developed such as battery storage, pumped storage, compressed air storage, etc. Germany has a pump storage capacity of 38 GWh, battery storage < 0.1 GWh, compressed air storage: 0.65 GWh [1]. Currently installed energy storage devices have not been designed to meet the demand of residual loads, but to collect cheap nuclear and coal power during the night and sell it during daily peak loads. With further installation of photovoltaic power plants and wind turbines, the original night-day cycle of pump storage is increasingly challenged. Technologies like pump storage, batteries or high-temperature heat storage are not suited to cover relatively long residual load events. They must rather be considered as options for short-term buffer storage. For example, in Germany pump storage plants can provide less than 10 GW capacity for about 4 h (Table 1). This is not enough to cover the residual load.

In order to resolve this situation, a variety of hybrid (solar/fossil) power plants with thermal energy storage have been proposed [2–6]. Concentrated solar thermal power generation (CSP) is a typical solution to this problem. It uses beam solar radiation as primary energy, molten salt as heat storage media and natural gas backup in order to produce electricity in the same way as conventional steam cycle power plants, but with much less fossil fuel input [3]. However, a conventional thermal power plant cannot easily be transformed into a CSP power plant at any geographic location. For example, Germany has an average daily direct normal irradiation of only about 2.8 kWh/m^2, while countries like Morocco (5 kWh/m^2) and Chile (7 kWh/m^2), where commercial CSP plants have been installed, receive much more direct solar irradiation [7]. Also, in most cases there is not enough land area available nearby the power plants to install the necessary concentrating solar thermal

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Table 1
Installed capacities within a model scenario proposed by Trieb and Thess [8] for a transformation of German power supply structures.

Model Year	2020	2030	2040
Renewable Power Plant Capacity (MW)			
Photovoltaic	48,500	107,500	135,000
Wind Onshore	56,500	70,000	75,000
Wind Offshore	8400	12,500	14,000
Hydropower	5700	5640	5640
Solid Biomass, Wood, Waste	3000	1800	0
Biogas, Energy Crops	4700	0	0
Geothermal Power	38	250	1000
Hydropower Imports	0	250	1000
Thermal Storage Power Plant Capacity (MW)			
TSPP Photovoltaic	0	52,500	105,000
TSPP Steam Turbines	0	10,500	21,000
TSPP Gas turbines	0	24,500	49,000
TSPP Heat Storage Capacity (GWh)		300	600
Fossil Power Plant Capacity (MW)			
Gas Turbines	1390	17,200	19,300
Hard Coal Power Plants	22,000	14,500	0
Combined Cycles and Combined Heat and Power	28,700	15,500	0
Other	5700	0	0
Nuclear Plants	9400	0	0
Lignite Plants	21,200	7000	0
Storage and Grid Capacity (MW)			
Pump Storage	9850	9850	9850
Net Transfer Capacity Import	27,000	27,000	27,000
Net Transfer Capacity Export	23,000	27,000	27,000

collectors, and heat from the solar field cannot be easily transported over long distance.

Another possible solution to the above-mentioned change of paradigm related to the residual load has been proposed recently in form of highly flexible thermal storage power plants (TSPP) [8,9]. Such plants use photovoltaic power, biomass and natural gas as primary energy sources in combination with high-temperature heat storage and conventional steam and gas turbines. Such plants provide secure, flexible and at the same time renewable power capacity and are able to cover highly variable residual load patterns. Using PV instead of CSP collectors as primary energy source allows to install the solar collector fields at higher distance to the power plant, because energy is transported in form of electricity instead of high temperature heat.

By transforming conventional power plants like coal, oil or gas plants to TSPP, their fuel consumption and related carbon emissions are reduced while their firm capacity is maintained and their flexibility is increased. Also, considering that all the thermal power plants will be changed from providing base loads to providing residual loads, biomass plants are also a good choice to be transformed. In case of transforming biomass plants to TSPP, scarce biomass is set free for other uses or for capacity expansion, making use of biomass as ideally stored form of renewable energy in order to cover the residual load.

The paper at hand shows a first conceptual approach to quantify the potential of existing conventional thermal power plants that could be converted to TSPP in a specific region, and identifies the necessary land areas that would be required for PV plants in their vicinity. The paper is organized as follows: chapter 2 presents the TSPP principle and its possible impact on German power supply in the frame of a scenario with 90% renewable electricity share, briefly summarizing a prior publication. Chapter 3 explains a ranking of existing German power plants with respect to a possible transformation to TSPP. This chapter also shows how the potential of greenfield PV installations in the vicinity of thermal power plants was assessed using a geographic information system that includes plant sites and different types of land cover. Finally, chapter 4 summarizes the preliminary results of this methodological approach, followed by conclusions in chapter 5 about its feasibility and an outlook for further work.

2. Theory

2.1. Thermal storage power plants for residual load supply

TSPP use photovoltaic power, biomass, synthetic fuels or natural gas as primary energy sources in order to supply electricity just as required by the residual demand. Layout of the plants and their components can be flexibly configured in order to optimally match demand related to the residual load in different regions of the world [8].

TSPP, as defined here, consist of a renewable energy source with a regular production cycle such as photovoltaics, heat storage with about 12 h of full load capacity corresponding to the average duration of the solar energy production cycle, a steam turbine powered by heat from that storage, a gas turbine that takes over extreme demand peaks, an electric heater and a backup heating unit as well as a waste heat recovery unit for the gas turbine's exhaust gas (Fig. 1).

The core of a TSPP is a thermal battery also called Carnot Battery [10,11]. In the configuration discussed here, it consists of an electric heater, a molten-salt thermal energy storage and a steam power cycle driven by heat from the storage. The efficiency of a thermal battery of this configuration lies in the order of 38%, accounting 95% for heater and storage and about 40% for the Ranking Cycle. Together with

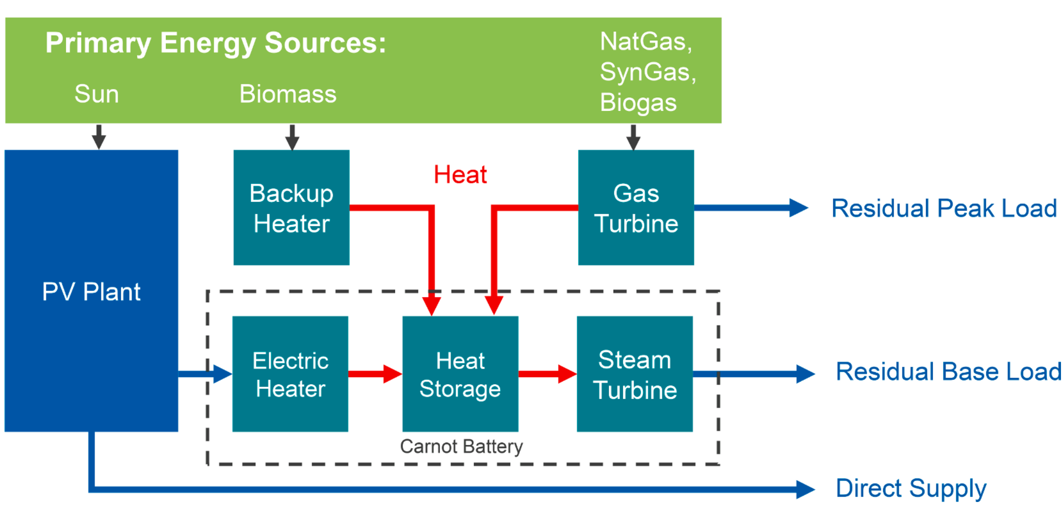

Fig. 1. Schematic of a TSPP: renewable power source, molten salt heat storage with electric heater and co-firing (solid biomass), steam turbine and additional gas turbine (fired by natural gas, syngas or biogas) with waste heat recovery. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

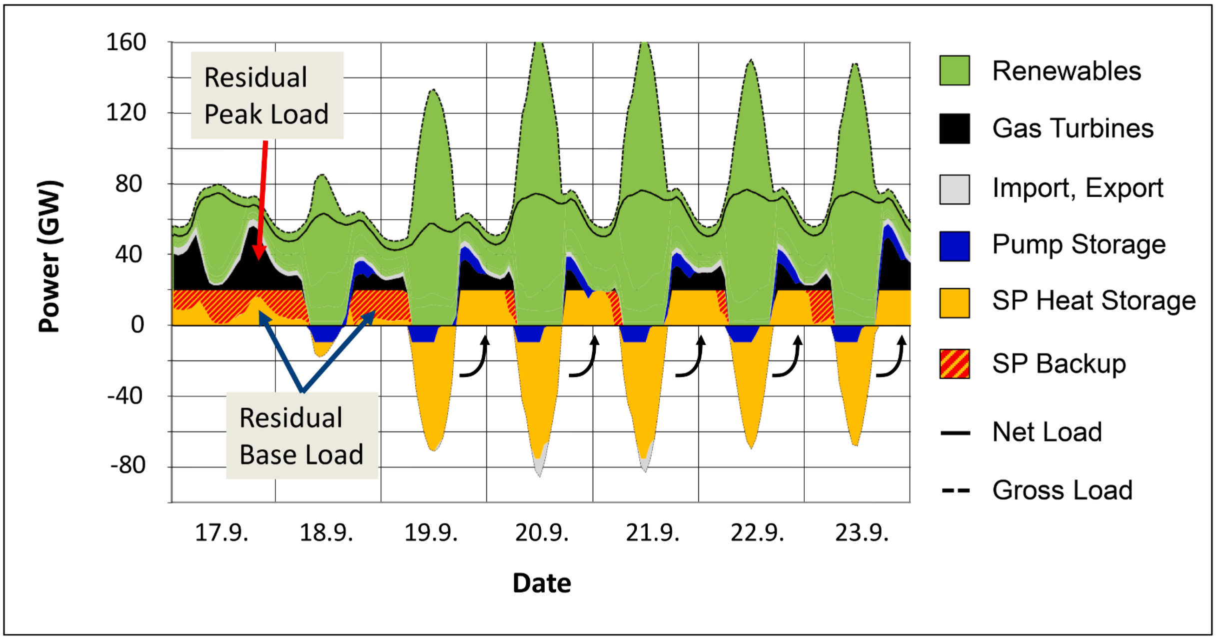

Fig. 2. One-week-sequence of annual hourly model time series of the German power supply system for the year 2040 with 90% renewable electricity share. Positive values indicate load, power production and imports. Negative values indicate power exported or fed to storage. Gross load includes power production used for system management as well as for power transmission and storage. Steam Turbines of TSPP produce electricity either from heat storage including stored PV and waste heat recovered from gas turbines or from biomass backup (please refer to the horizontal line at 21 GW that marks the installed steam turbine capacity of the TSPP. The term “residual base load” used here does not mean uninterrupted power generation, as storage operation is alternating with direct generation from renewables. It just refers to the “lower” supply band of the TSPP’s steam turbines with much higher hours of utilization than the peaking gas turbines. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 2
Ranking criteria of existing power plants for a transformation into TSPP applied here.

Power Plant Properties	Score		
	①	②	③
Age	< 20 y	20–40 y	> 40 y
Power Plant Capacity	< 250 MW	250–500 MW	> = 500 MW
Steam Temperature	< = 560 °C	560–600 °C	> 600 °C
Fuel	Biomass	Fossil fuels	-

Table 3
Ranking levels of the power plants based on the scores from Table 2.

Scores				Ranking Levels
①	②	③	Total	
4	-	-	4	A
3	1	-	5	B
3	-	1	6	C
2	2	-	6	C
2	1	1	7	D
1	3	-	7	D
2	-	2	8	E
1	2	1	8	E
-	4	-	8	E
1	1	2	9	F
-	3	1	9	F
1	-	3	10	G
-	2	2	10	G
-	1	3	11	H

biomass backup and waste heat recovery from the gas turbines, the Carnot Battery with the steam turbine is in charge of securely covering the base load segment of the residual load curve, alternating operation with direct supply from renewables (Fig. 2).

As a significant part of PV electricity can be delivered directly to consumers without any storage losses, the average weighted power-to-power efficiency of transforming variable PV into electricity on demand lies in the order of 55–75%, depending on the share of direct supply that can vary between 30 and 60%.

Electricity generated by such plants under residual load conditions typically stems by about one third from PV, one third from biomass backup and one third from the peaking gas turbines fired by natural gas, with a significantly lower carbon footprint than that of conventional thermal power plants providing equivalent services [8]. In the long-term also the gas turbines can be fired by biomethane or synthetic natural gas from renewable production, finally reducing carbon emissions to zero.

It has been discussed to use a high temperature heat pump instead of the electric heater in order to achieve a better efficiency of the Carnot battery [12]. However, this technology is not yet state of the art, and its cost and efficiency are yet difficult to define. For this reason, a more conservative approach with electric heater was used [8].

TSPP as discussed here hypothetically allow for considerable expansion of national PV capacity without creating any fluctuations on the grid, but on the contrary covering the increasingly problematic residual load in a very effective, secure and economic manner.

2.2. German electricity sector scenario with thermal storage power plants until 2040

When talking about a transformation of conventional thermal power plants to TSPP, a central question is where to find enough land area for the PV plants that are supposed to substitute the fossil fuel formerly used as primary energy in those plants.

Trieb and Thess [8] have recently proposed a possible transformation of the German electricity sector until 2040 towards a renewable energy share of 90% making use of TSPP to cover the residual load. In their hourly time series model, TSPP consist of a total of 21 GW steam turbines and 49 GW gas turbines, 105 GW photovoltaics and heat storage with 600 GWhth storage capacity equivalent to about 12 h of

Table 4
Some examples of the ranking results of the power plants in Germany (input data from World Electric Power Plants Database (WEPP) [14] and Global power plant database (WRI) [15]).

Unit	NEUFAHRN STEAG 1	HKW MEUSELWITZ 1	SCHIRRHOF 1	ZOLLING 5	BERGKAMEN A
Latitude (°)	48.314	51.042	49.992	48.4554	51.637
Longitude (°)	11.661	12.302	8.247	11.7995	7.619
Capacity (GW)	5.3	5.4	6.5	474	777
Year of start-up	2004	1997	1981	1985	1981
Steam Temperature	455	420	450	535	530
Fuel	Biomass	Biomass	Gas	Coal	Coal
Score Capacity	①	①	①	②	③
Score Age	①	②	②	②	②
Score Steam Temperature	①	①	①	①	①
Score Fuel	①	①	②	②	②
Ranking Level	A	B	C	D	E

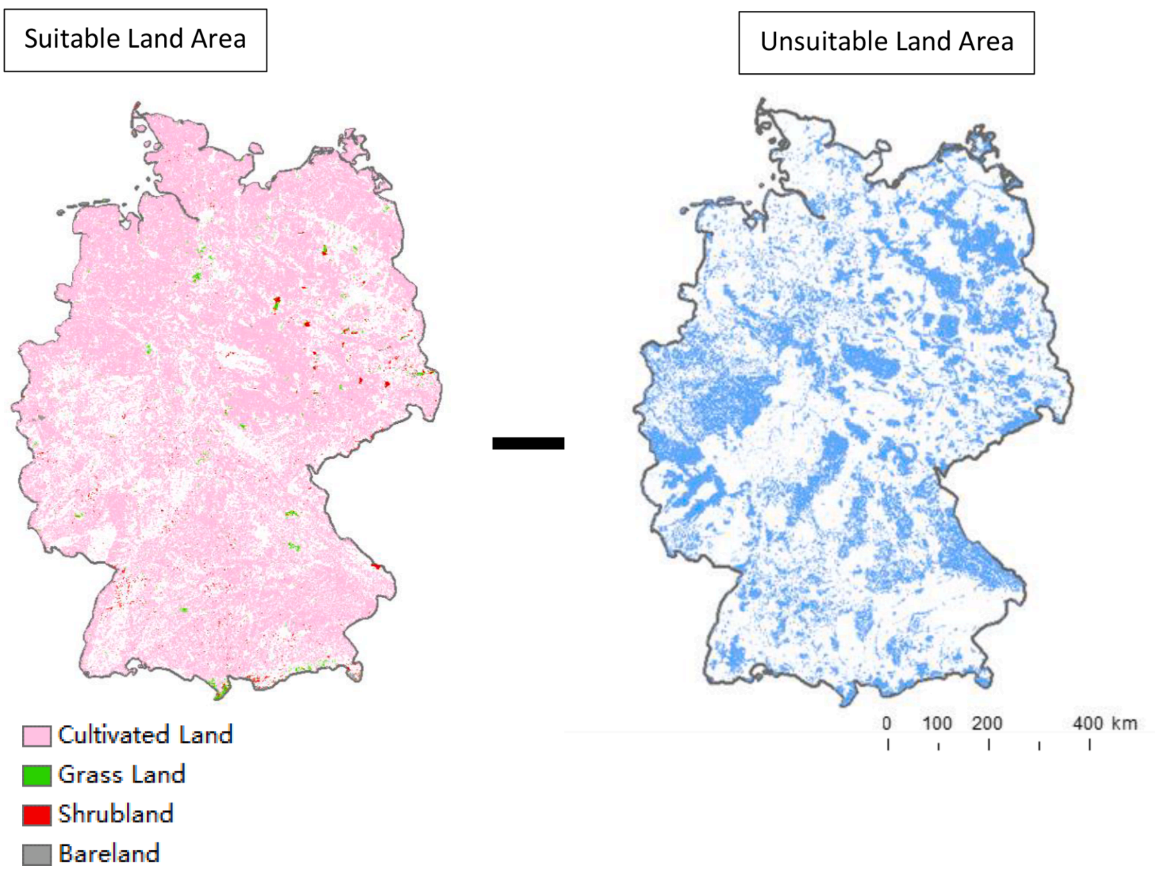

Fig. 3. Land cover information in Germany: Left: Suitable areas for PV installation (Source: GlobeLand30 Land Cover Database [19]). Right: Exclusion areas for PV installation in Germany (Source: Digital Soil Map of the World [27] (not shown in this figure, because there's no sand dunes and glaciers), World Topographic Map [23], Global Lakes and Wetlands Database [24], World Database on Protected Areas [26], Global Roads Open Access Data Set [25]). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

maximum power output of the steam turbines (Table 1). Assuming a typical land use of 0.015 km^2/MW [13], a total land area of 1575 km^2 is required for the PV plants needed to power the TSPP that are considered within this transformation scenario.

In this scenario, biomass is used for residual load purposes rather than being burned in continuous base load operation, which means that conventional biomass plants are also converted to more flexible TSPP. In spite of doubling capacity from present 10 GW biomass plants to over 20 GW TSPP, the overall biomass consumption for electricity can be kept constant within this transformation pathway thanks to high shares of PV power delivered to consumers either directly or through the heat storage. As a consequence, land area required for biomass backup of future TSPP is not higher than that required for today's conventional biomass plants. In TSPP, biomass contributes much more to increase the flexibility of the power sector than in conventional biomass plants that up to now are rather operated in base load.

The time series analysis of that model reveals that during longer residual load events, the residual load is mainly covered by co-firing the steam turbines of the TSPP with biomass and by the peaking gas turbines (Fig. 2, to the left).

When the load exceeds the maximum steam turbine capacity (here 21 GW), peaking gas turbines are activated and provide waste heat for the storage, reducing biomass consumption. During longer residual load events, steam turbines operate continuously in base-load. Such situations occur more frequently and over longer periods (up to two weeks) in winter. On most other days, steam turbines, eventually complemented

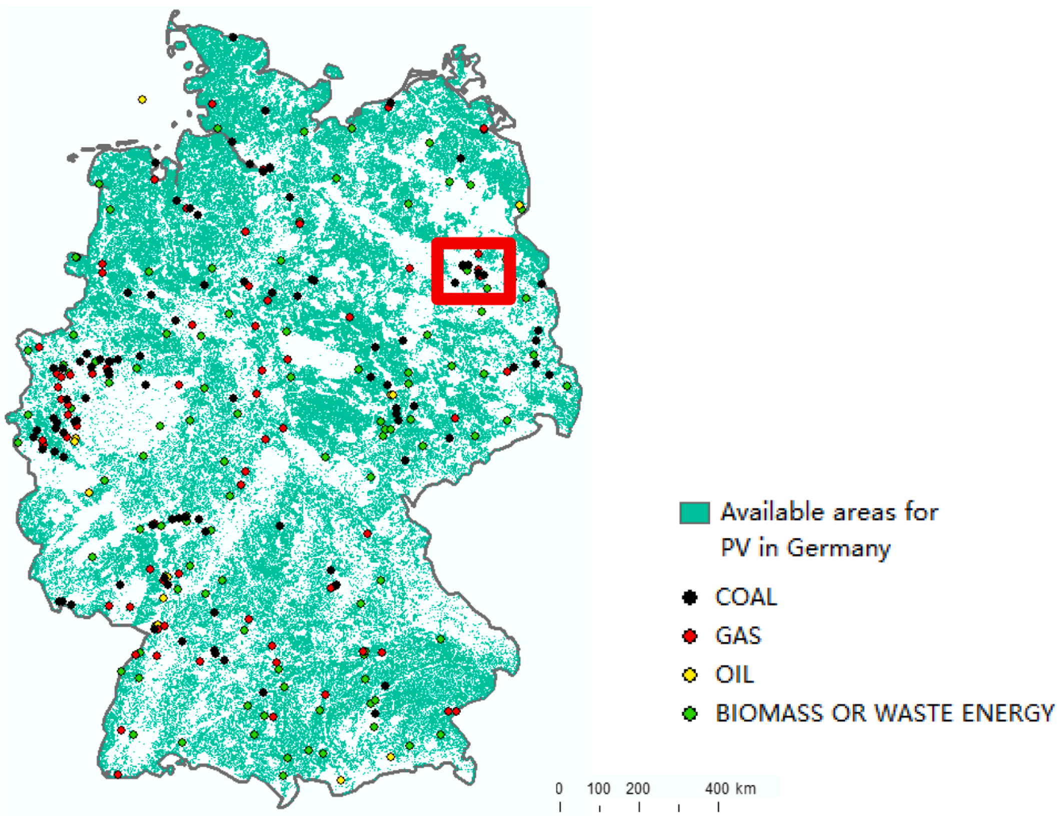

Fig. 4. Selected power plants and potential areas for PV installation in Germany considering agricultural land as suitable. The red square defines an area that was selected for a closeup of the exemplary results shown later in Fig. 9. The total theoretically available area amounts to 162,541 km^2. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

by peaking gas turbines, alternate with direct supply from photovoltaic power production. During daytime, PV power totally covers the demand and produces surplus on top. It can be appreciated how regular electricity surplus from photovoltaic generation can be effectively stored in pumped hydro and heat storage facilities, and how the likewise regular supply gaps of the residual load curve can be easily filled by the TSPP including steam and gas turbines.

Thanks to the high solar share and to waste heat recovery from the peaking gas turbines, the consumption of fuel (in this case biomass and natural gas), that is ultimately required for firm capacity, is significantly reduced. In fact, this is what finally makes the use of scarce biomass for that purpose feasible, because otherwise, German biomass resources would be over-used. The plant's configuration and the fuels used can be adapted to any situation worldwide, providing a possible key element of a global transition towards renewable energy in the power sector. More details of this scenario can be found in [8]. For our further analysis, this scenario defines and quantifies the amount of conventional power capacity to be transformed to TSPP and the required additional PV capacity to be installed as part of them.

3. Methods

3.1. Ranking of existing thermal power plants for a transformation to TSPP

From the World Electric Power Plants Database (WEPP) [14] and the Global Power Plant Database of the World Resources Institute (WRI) [15] about 450 different power plant units have been identified in Germany using fossil fuels. In order to figure out which power plants are best suited for a transformation to TSPP, a set of evaluation criteria has been created in order to generate a theoretical priority list. The purpose of this ranking is a first rough pre-selection of power plants based on model assumptions. It does not substitute the analysis and discussion about concrete individual projects. It rather aims to help developing a general strategy for such transformation and to assess its feasibility. Selection criteria applied here can be further extended and fine-tuned in future work.

In a first approach four criteria were considered for ranking existing power plant units (Table 2):

- Operating years: A period of 20 years is set as threshold to classify power plant units by their age. If the units are less than 20 years in operation, it is considered that these units can still operate for a long period of time and have a high added value from transformation. Units that have an age between 20 and 40 years have less priority and thus get a score of 2. The rest of them have the lowest added value from renovation, so they only get a score of 3.
- Another important ranking factor is the power plant capacity. When transformation is carried out for a power plant, photovoltaic capacity required is often several times that of the steam turbine (in our Case 5 times larger). Oversizing is necessary due to the relatively low efficiency of the power cycle (about 40%) and to achieve reasonably high utilization of the heat storage (about 2000 h/a). Therefore, when the capacity of the power plant is very high, the area required for photovoltaics can become extremely large. Plants with a capacity of less than 250 MW are considered here as most suitable and highly ranking. A capacity between 250 and 500 MW gets a score of 2, assuming the size of the required PV areas is still acceptable. Plants larger than 500 MW get a score of 3.
- The third criterium is the life steam temperature of the Rankine cycle. The reason is that molten salt heat storage tanks cannot be operated above 560 °C [16]. When the temperature is higher than 560 °C, other heat carriers like particle suspensions could replace molten salt in a TSPP. According to the calculation from Zhang et al.

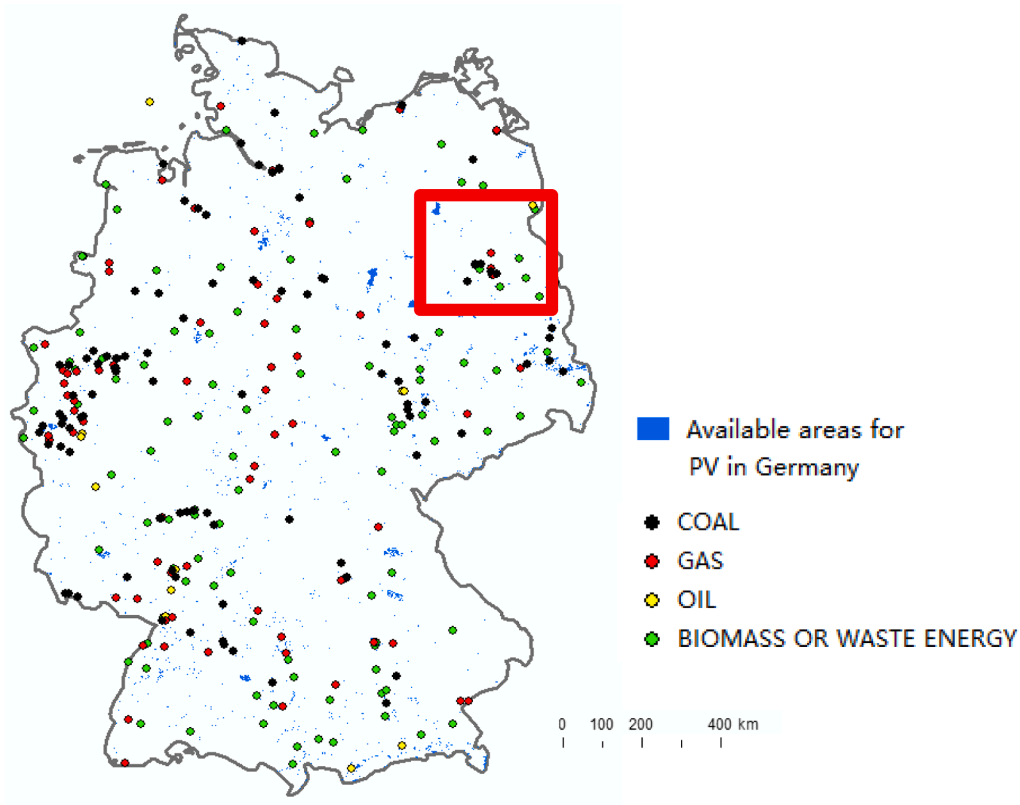

Fig. 5. Selected power plants and potential areas for PV installation in Germany excluding agricultural land. The red square defines an area that was selected for a closeup of the exemplary results shown later in Fig. 10. The total theoretically available area amounts to 2710 km^2. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

[17], although additional costs are needed for the materials and for appropriate boilers, cost could be lower than that of molten salt. Solid state storage with air as transport medium could also be used and is already under development [18]. Within this paper, in a conservative approach and considering state of the art technology, we assume that TSPP operating at temperatures lower than 560 °C with molten salt get the best score due to their proven availability and maturity.

- The last criterium relates to the fuel type of the power plants. Being an ideally stored form of renewable energy, biomass has highest priority to guarantee firm capacity and flexibility of TSPP and gets priority 1, while fossil fuels such as coal, oil and gas get priority 2.

Table 2 shows an overview of the ranking criteria applied here. After the evaluation, a final score based on the number of high and low scores of the power plant units was calculated in order to obtain the overall ranking of thermal power plants in Germany. Table 3 shows the resulting ranking levels based on the different scores.

Table 4 shows some examples of the ranking results. Five power plants were chosen just to illustrate examples of the different ranking levels. With the method above, all steam turbine power plant units are assigned to different ranking levels. The higher the ranking-level the unit has, the higher priority of assigning the necessary PV installation areas it will have.

It should be noted that the ranking criteria that have been chosen here and their scoring must be considered as a first approach to test this methodology and to get preliminary results in order to assess its feasibility and to develop further guidelines for fine tuning. The results described later are only valid under the frame conditions and assumptions used here and could be modified in further investigations.

3.2. Renewable energy potential for use in thermal storage power plants

An important task is to identify available land areas for PV installation in a certain country or area to make a transformation of thermal power plants possible. PV is particularly well suited to substitute fossil fuels in TSPP, because world-wide, solar energy has a regular daily cycle of roughly 12 h of availability and 12 h of non-availability. While fossil fuel like coal, oil or gas is a form of ideally stored energy that does not need any regular cycle for charging and discharging, the heat storage used in TSPP, being a buffer storage rather than an ideal energy storage like fossil fuel, certainly does. While ideally stored energy in form of fossil fuel or biofuel is the only way to guarantee firm capacity at any time, the use of a buffer storage fed by regularly cycling solar energy can significantly reduce, but not completely substitute annual fuel consumption. TSPP make use of both types of storage: ideally stored fuel for firm capacity and heat (buffer) storage just to reduce annual fuel consumption.

Technically suitable land area for PV installation was derived from the GlobeLand30 Database [19] that classifies 10 different types of land cover. Special software was used to process geographic information (ArcGIS [20]; QGIS [21]). Within the work described in this paper, only the following land cover classes were considered as suitable for potential PV installation in order to avoid possible conflicts with sensitive areas like forests or urban land [22]:

- Cultivated Land
- Grassland
- Shrubland
- Bareland

Left side of Fig. 3 shows suitable land properties for PV installation as well as their geographic distribution in Germany. Land properties such

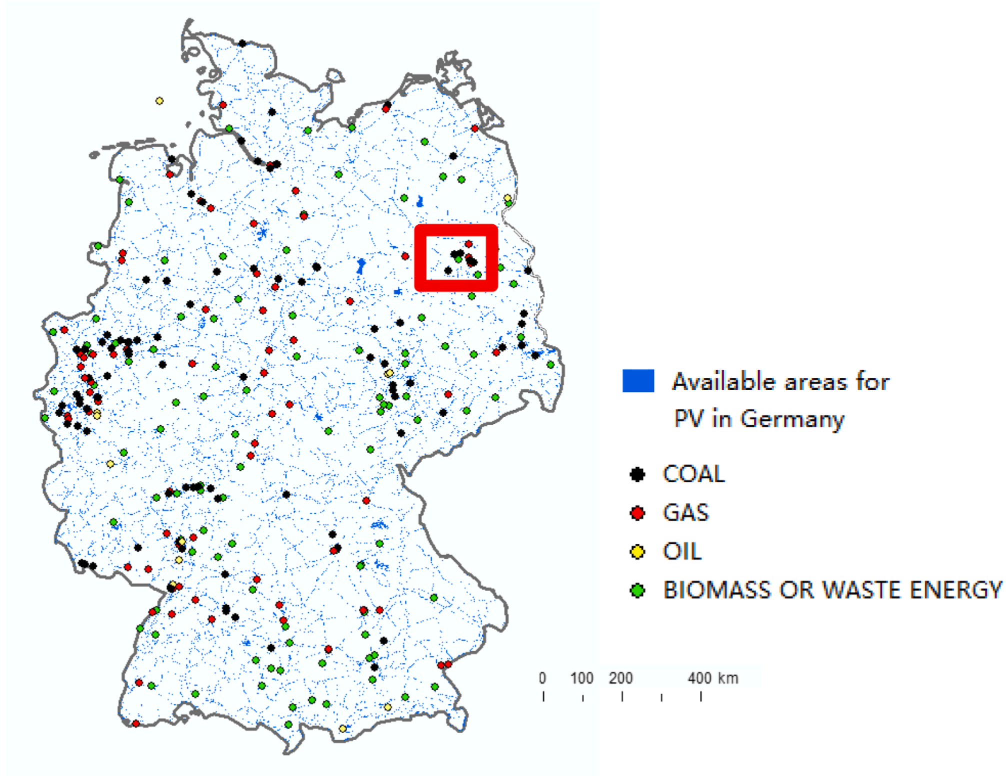

Fig. 6. Selected power plants and potential areas for PV installation in Germany including agricultural land with 200 m distance alongside the highways. The red square defines an area that was selected for a closeup of the exemplary results shown later in Fig. 11. The total theoretically available area amounts to 15,236 km^2. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

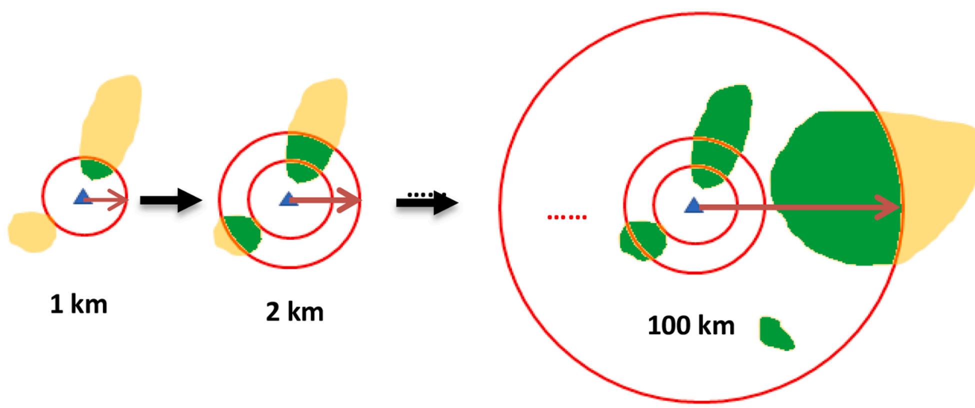

Fig. 7. Algorithm of finding suitable PV areas for a power plant unit. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

as very steep terrain identified by the World Topographic Map [23], wetlands, lakes and rivers from Global Lakes and Wetlands Database [24], major roads from Global Roads Open Access Data Set [25], and protected areas from the World Database on Protected Areas [26] were additionally excluded for PV installation (blue area in right graph in Fig. 3).

The algorithm can be programmed considering different levels of limiting the potential PV area for TSPP: firstly, including agricultural land, secondly, excluding agricultural land and thirdly, including agricultural land only alongside main roads, in order to limit its visual impact on the landscape.

Fig. 4 finally shows the resulting land area that in principle can be used in Germany for PV installation considering agricultural land as suitable, as well as the locations of selected power plant units. In this case the PV potential of more than 160,000 km^2 would be much larger than the area of 1575 km^2 required for the reference scenario described before.

For comparison, Fig. 5 shows the result excluding agricultural land for PV installation. The PV potential of 2700 km^2 would be sufficient but significantly smaller, and suitable areas might only be found at much larger distances from the existing thermal power plants.

Fig. 6 shows the results considering cultivated land only alongside the main roads. In this case a distance of 200 m of cultivated land on both sides of the highway is considered as potential PV area [13]. The resulting potential of 15,000 km^2 would still be about ten times larger than the area required for the reference scenario.

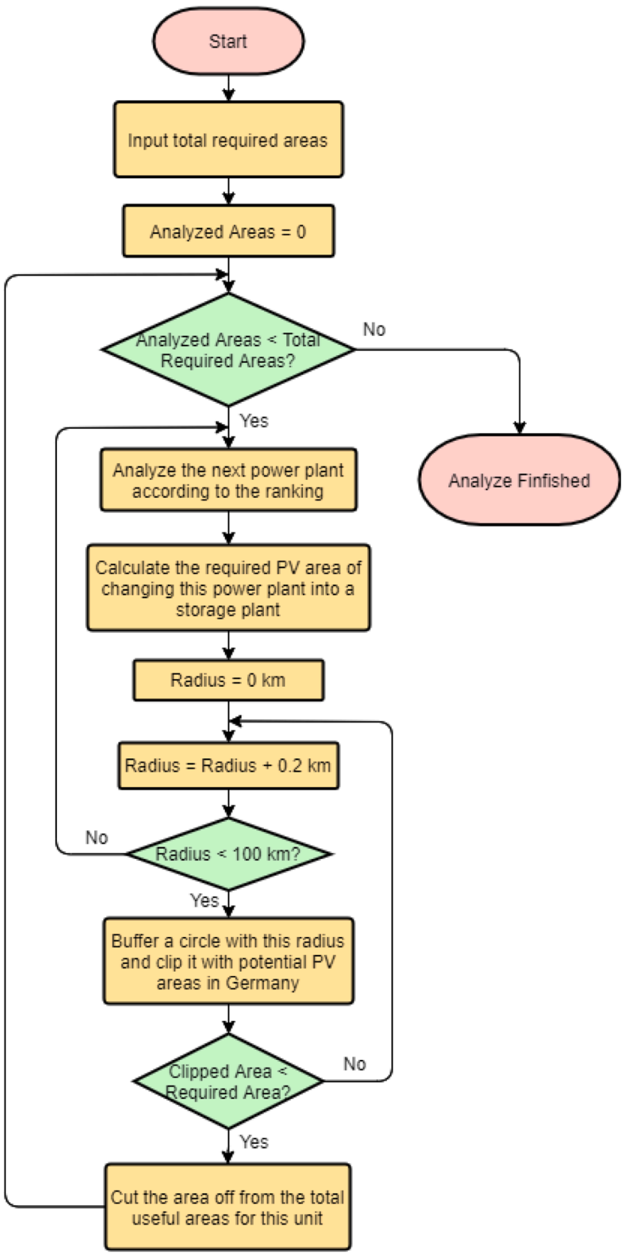

Fig. 8. Algorithm of assigning suitable land area for PV installation to each power plant unit. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 5
Result with agricultural land of the transformed power plant units in Germany by fuel type. The scenario described above requires a total of 21 GW of steam turbines to be transformed to TSPP until 2040.

	Steam Turbine			Combined Cycle		
	Capacity (GW)	Number	Used Areas (km^2)	Capacity (GW)	Number	Used Areas (km^2)
Coal	16	106	1151	–	–	–
Oil	0.6	21	50	–	–	–
Biomass	1.2	131	107	–	–	–
Gas	2.0	66	153	1.5	5	114
Total	19.8	324	1461	1.5	5	114

3.3. Algorithm relating PV areas to thermal power plants

In this section, the algorithm relating potential PV areas to single thermal power plants is explained. According to the transformation scenario described in Table 1, an amount of 21 GW capacity of steam turbine power plants must be transformed or newly erected as TSPP including 105 GW photovoltaics as primary energy source. This requires about 1575 km^2 of land area for greenfield PV system installation. This means that in all three cases of limiting PV potential described before, enough land for PV installation is available in Germany in order to realize the reference scenario.

Fig. 7 shows an example explaining the algorithm of how land areas for PV installation are found for a specific power plant unit. A circle with variable radius of 1–100 km is drawn around each TSPP and the circle is overlapped with the potential PV areas in the region (marked yellow). Then the common area is calculated as a potential PV development area for this specific TSPP (marked green). If this area is bigger than the PV area required by the power plant, sufficient area has been found and the algorithm is stopped. If not, the radius will be extended by 1 km, a larger circle will be drawn, a larger overlapping area will be calculated, another comparison with demand made, and so on. If the radius becomes eventually larger than 100 km, but the overlapping area still cannot fulfill the demand of the power plant, we consider this power plant as not suitable to be transformed into a TSPP, and it is set to a lower priority on the ranking list. In order to calculate that function automatically, a Python program has been set up that works together with ArcPy toolbox from ArcGIS. This program can be adapted to rank power plants for different countries. The ranking criteria can also be changed to fulfill different geographic conditions for each country.

The flow chart in Fig. 8 shows a more detailed explanation of how the algorithm of the program works. Firstly, the total required PV area of 1575 km^2 required for the TSPP is set as input of the program according to the scenario described above. Then the Python algorithm will pick up the first power plant unit in the ranking list and start the first loop. Once the suitable areas for this plant are found, the overlapping (green) area will be cut off from the suitable (yellow) areas. Lower ranking plants will only have access to the remaining area. When the program arrives at a radius of 100 km and still has not found enough land area for PV, the program will go for the next power plant unit in the ranking list, and the area found for the discarded plant will not be cut off.

If the available areas are larger than the total required areas for all scheduled TSPP, the program will finish, which means that no further TSPP have to be built, and that the transformation of the power plants considered up to that point can already fulfill the scenario demands. If all the power plant units in the ranking list in one country are analyzed by the program and the whole calculated areas are still smaller than the total required areas (usually because that many power plant units in the ranking list are skipped for not having enough PV land areas), then it means that the analysis is not successful, the planned energy scenario cannot be fulfilled, and possibilities of installing PV on other land areas must be considered.

4. Results and discussion

4.1. PV area potential including agricultural land

In the first assessment agricultural land was included as potential site for PV plant erection. About 330 power plant units were selected by the algorithm to be transformed into TSPP with enough areas to build photovoltaics nearby. The statistical analysis in Table 5, top shows that about 16 GW coal power plants, 2 GW gas plants and 1.5 GW Combined Cycle Plants could be transformed to TSPP. The total transformed capacity is 21.3 GW, which fulfills the goal of the scenario for the year 2040 described above. The area required for PV installation is 1575 km^2, which is 0.43% of the total land area of Germany. This number includes about 1500 km^2 of agricultural land. Bi-facial agricultural PV systems

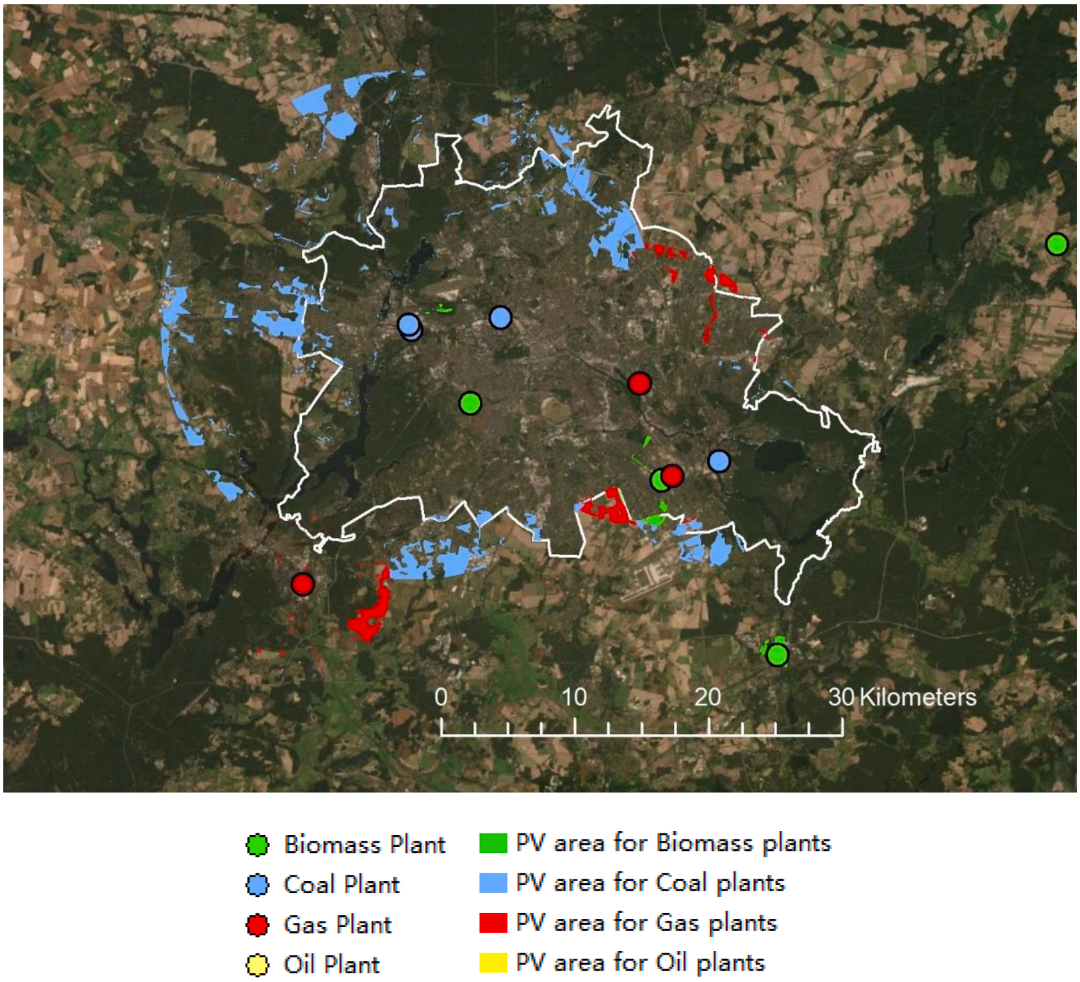

Fig. 9. Power plants selected for transformation to TSPP and related PV areas in Germany including agricultural land and considering Agro-PV technologies (Closeup from Fig. 4) [20]. The closeup contains all PV areas needed for transformation of the selected power plants. Most areas have been found outside the city limits. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 6
Numerical result of PV area assessment without considering agricultural land.

	Steam Turbine			Combined Cycle		
	Capacity (GW)	Number	Used Areas (km^2)	Capacity (GW)	Number	Used Areas (km^2)
Coal	17.6	112	1267	–	–	–
Oil	0.9	25	68	–	–	–
Biomass	1.2	134	98	–	–	–
Gas	1.8	70	136	0.084	2	6
Total	21.5	341	1569	0.084	2	6

may allow for a simultaneous use of agricultural land for crop raising and photovoltaic power generation and show different – eventually more favorable – daily production patterns [28]. Fig. 9 shows part of the analysis result in the capital city of Berlin and its surroundings. As seen in this picture, most of the PV areas can be found outside the city borders. The analysis result from ArcGIS shows in this case that the average distance between PV plants and the related thermal power plants in Germany is about 3 km. Coal power plants with high capacity obviously need a larger area for PV installations than other, smaller plants.

4.2. PV area potential excluding agricultural land

A second analysis was made to test if there would be enough potential area for PV installation without making use of cultivated land to fulfill the demand of the transformation scenario (Table 6). From the total of 453 thermal power plants in Germany, about 343 power plant units with 21.5 GW capacity were chosen to be transformed, which also fulfills the transformation goal.

Fig. 10 shows the selected power plants and the potential area for PV installation found in the surroundings of the city of Berlin. The distances to the required PV sites are much higher than in the example including agricultural land. In case of not using agricultural land, the average distance between PV plants and thermal power plants increases to 25 km, and the potential PV plants are much more scattered. In Germany, the additional use of agricultural land for PV installation would have a significant added value for a transformation of conventional power plants to TSPP.

4.3. PV area potential including agricultural land only along main roads

In the discussion about potential PV areas in Germany it has been suggested to use agricultural areas preferably alongside the highways [13]. This can be considered as compromise between the concepts described in chapters 4.1 and 4.2. For this reason, another analysis was made. This time, agricultural areas with 200 m distance alongside main roads are considered as potential PV areas (Fig. 6).

The result of this analysis shows a total of 354 power plants to be transformed (Table 7). The average distance from each power plant to the related PV area in Germany is just about 6 km, and the maximum

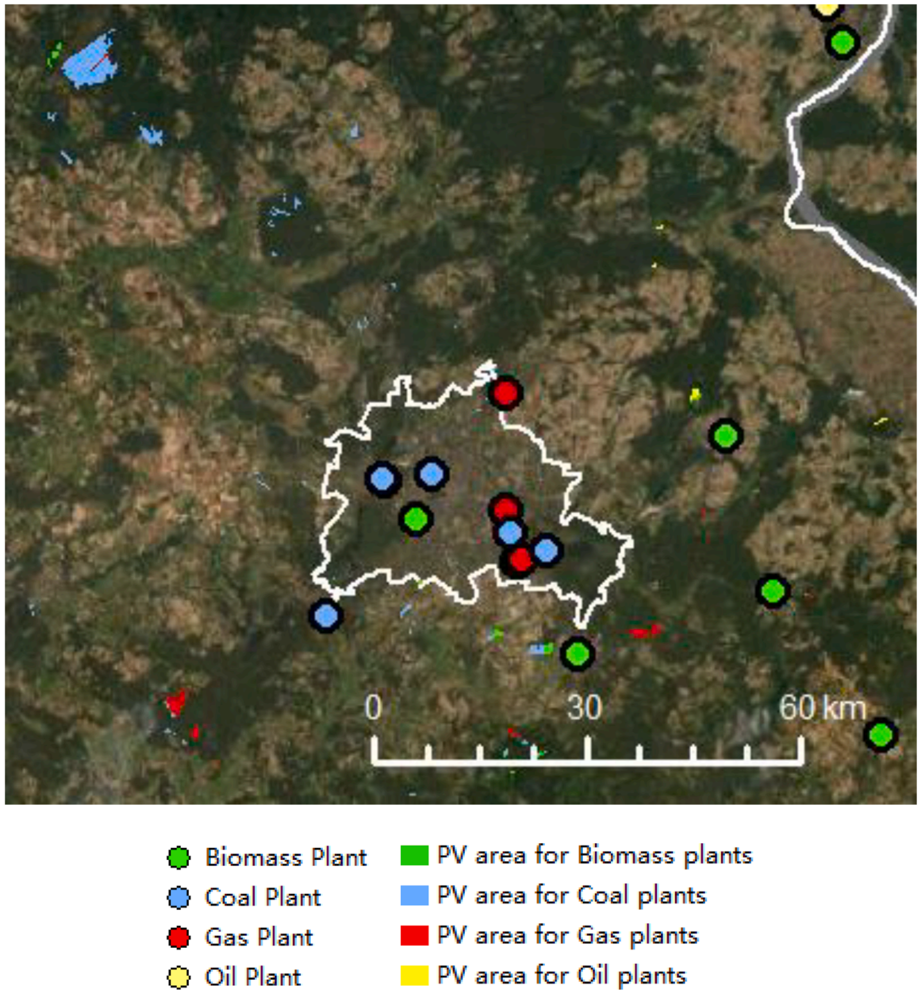

Fig. 10. Power plants and related PV areas in Germany excluding agricultural land (Closeup from Fig. 5) [20]. There is not enough PV potential for the power plants near the city border of Berlin and the average distance between power plants and the required PV plants increases significantly. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 7
Result of potential PV area assessment including agricultural land only along main roads.

	Steam Turbine			Combined Cycle		
	Capacity (GW)	Number	Used Areas (km^2)	Capacity (GW)	Number	Used Areas (km^2)
Coal	14.7	108	1134	–	–	–
Oil	0.9	26	73	–	–	–
Biomass	1.3	134	111	–	–	–
Gas	2.3	80	191	2	6	150
Total	19.2	348	1509	2	6	150

distance is about 52 km, which is acceptable. Fig. 11 shows the thermal power plants in or near Berlin as well as their corresponding PV areas. As shown in the picture, the PV areas found with this algorithm reveal a typical ring structure around areas with high population density like the city of Berlin.

5. Conclusions and outlook for further work

The ranking algorithm used here mainly selects coal and lignite plants for a transformation to thermal storage power plants (TSPP) until 2040. This complies with the decision of the German government to phase-out coal plants until 2038 in order to reduce carbon emissions of the power sector. Although combined-cycle gas plants and biomass plants can also be transformed to TSPP and even may have a higher ranking due to a relative easiness of such transformation, their carbon emissions and the related motivation for their transformation are lower. However, in the long-term, their flexibility must be clearly enhanced in order to cope with the expected residual load requirements, making them also interesting candidates for such transformation. Moreover, the reference scenario used here reveals a huge demand of future gas turbine capacity, which is fully in line with the above said.

Considerable land area of about 1575 km^2 is theoretically needed for PV installations to transform the required power plant units in Germany to TSPP and to substitute the related fossil fuels. Although the used method has identified enough potential land area for such transformation, general acceptance of such huge additional land use may be critical. New developments of PV technologies must be taken into consideration in order to reduce pressure on the land environment and to avoid long distances between power plants and PV facilities. If agricultural land can additionally be used for PV, it will help to transform even large coal power plants to TSPP and at the same time create additional income for farmers.

In the future, updated versions of the described data set as well as the related geographic information will be used to increase the accuracy of calculation with updated information about power plants, land use and suitable areas for PV installation.

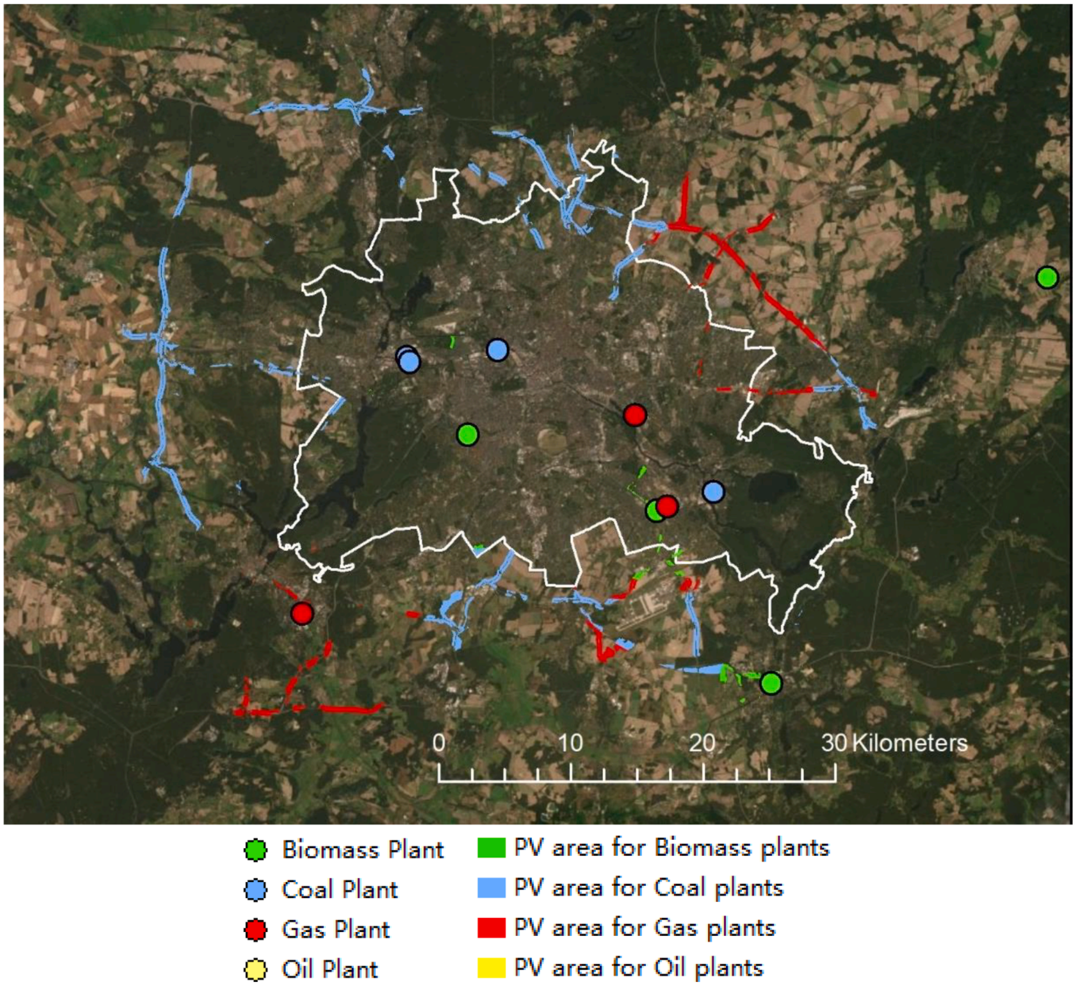

Fig. 11. Power plants selected for transformation to TSPP and related PV areas around the city of Berlin including agricultural land at 200 m alongside the highways (Closeup from Fig. 6) [20]. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

The ranking criteria of the thermal power plants are still under discussion and will be updated and optimized in the future. There are also further possibilities to optimize the analyzing algorithm, for example, the idea of setting a bigger radius to find the suitable areas for PV until it fulfills demand is under discussion. Using cultivated land only alongside main roads could be a viable compromise for large scale PV installations. Further environmental conditions will be taken into consideration and improvements will be made to the program algorithm so that a more accurate transformation plan will emerge.

This method can not only be applied to Germany, but also can serve as example for other countries in the world. The solar resources of Germany are not among the best worldwide. Therefore, further analysis of sunny regions like Chile, Australia or North Africa may reveal the feasibility of a transformation of thermal power plants to TSPP under even better conditions.

CRediT authorship contribution statement

Pai Liu: Methodology, Software, Formal analysis, Writing – original draft, Funding acquisition. **Franz Trieb:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

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Paper II: Cost comparison between conventional power plants and transformedTSPP

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The contribution of this paper is described as follows:

Pai Liu: Methodology, Software, Formal analysis, Investigation, Writing – original draft.

Franz Trieb: Conceptualization, Methodology, Validation, Supervision, Review & editing.

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Research papers

Cost comparison of thermal storage power plants and conventional power plants for flexible residual load coverage

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ABSTRACT

The paper presents a cost comparison of thermal storage power plants (TSPP) with various conventional power plants. TSPP require less fuel and can better fulfill the demand of variable and intermittent residual loads through providing a much higher flexibility with their intrinsic heat storage system, also called Carnot Battery. Due to reduced or completely avoided usage of fossil fuels, TSPP satisfy the goal of reducing greenhouse emissions in the current world. When comparing the LCOE of conventional power plants, such as biomass, coal, gas turbine and combined cycle power plants mentioned in this paper, with TSPP, the electricity cost of TSPP is lower than that of conventional power plants, no matter if they are newly built or obtained from converting existing plants. TSPP represent an effective hedge against the escalation of fossil fuel market prices as well as against rising CO_2 cost additions. The comparison indicates that TSPP under current conditions are the most cost-effective way to produce highly flexible power on demand.

1. Introduction: background and motivation

With the global need of decreasing greenhouse gas emissions, many countries have been shifting the focus of their energy strategy away from constructing new traditional thermal power plants towards renewable power generators, such as PV and wind power. However, while variable renewable power plants account for an increasing percentage of total power generation, reliably covering the remaining residual load is becoming a growing challenge.

As countries continue to promote sustainable energy policies, power from oil, gas and coal will be replaced by renewable sources. On the other hand, secure, firm and flexible power capacity – up to now provided by conventional plants on the basis of oil, gas and coal – will still be needed in the future. The trend towards variable and intermittent residual loads makes TSPP a viable option for flexible electricity supply.

TSPP are steam power plants that operate very flexibly because of a built-in heat storage. TSPP can absorb fluctuating electricity from renewable sources, store it in form of heat, and release it again into the network as required. Fossil fuels or renewable fuels such as biomass can deliver the necessary thermal backup power to the steam turbine in order to ensure reliable power supply at all times, also during irregular periods without wind and sunshine [1–3].

Fig. 1 shows a simplified schematic of a typical TSPP. Electricity from a large photovoltaic collector field is primarily delivered directly to the network and only stored when there is no demand for it. This strategy yields a surprisingly good power-to-power efficiency for solar electricity that can reach up to 70 %, defined by the weighted average of fractions directly supplied to consumers (without storage losses) and stored fractions (about 50/50), considering typical storage efficiencies of Carnot batteries with electric heater of about 40 % [4,5]. The overall loss of approximately 30 % can be considered as the price of transforming variable solar power into dispatchable solar power that can be delivered to consumers just on demand. Nevertheless, firm capacity and secure supply can only be provided by fuels, because a heat storage can run empty. In this context, the core function of the PV generator and the Carnot battery is to save as much fuel as possible, while the core function of fuels is to guarantee supply.

Another factor that speaks for TSPP is their high flexibility obtained from the integrated heat storage. The storage allows to adapt relatively slow combustion processes to highly dynamic residual load situations that characterize most supply systems with high variable renewable energy share. Despite of the fact that TSPP have significant advantages compared to conventional power plants, from a decision maker's perspective, price and cost are, and will always be one of the most

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important indicators. In the past decades, conventional power plants have been considered to be more cost effective than renewable power plants due to lower investment and fuel costs (e.g. comparing with biomass and biogas).

Because of speculations and political disruptions, world market prices of fossil fuels have lately increased dramatically. Fig. 2 shows the market price of natural gas, oil and coal in the past 3 years [6]. The highest price is more than three times more expensive than that in July 2019. Under extreme fuel price escalation some plants will have to temporarily stop generating electricity, which places an additional burden to reliable grid operation. This dramatic price fluctuation has put significant pressure on the economic performance of conventional power plants. Nuclear and lignite plants can produce electricity at lower cost, but they are not capable of covering highly variable and intermittent residual load patterns.

In order to hedge against the severe impact of rising energy prices, in the past few months, advanced progresses have been made on various types of renewable power plants. New technologies have been developed on solar thermal power plants such as concentrating solar power (CSP) or integrated solar combined cycle plants [7–9].

In contrast to TSPP, CSP power plants have higher efficiency when converting solar energy to heat, which is about 50 % annual average, while the efficiency of PV converting solar energy to electricity is only about 20 %. However, the concentrated heat from CSP must be sent to the steam turbine to generate electricity, significantly reducing the overall efficiency of power generation. Compared to CSP, PV collectors have following advantages:

- PV convert both the direct and diffuse solar radiation to electricity and can thus make use of a larger primary solar energy resource than CSP.
- PV panels are cheaper than solar thermal collectors comparing square meter prices.
- Operation of PV collectors requires less parasitic power than CSP collectors.
- In contrast to heat from CSP collectors, electricity from PV can be used directly without interim conversion to heat.

As a result of those advantages, the introduction of solar thermal power plants with PV collectors instead of concentrating solar thermal collectors has become a viable alternative. TSPP are nothing else but that.

The introduction of CO_2-cost and/or CO_2-taxes represents a significant burden to conventional power plants. TSPP, on the other hand, has no additional cost for this, as locally available, renewable primary energy is preferably used. These factors lead to a fundamental change of paradigm when comparing power generation costs from conventional power plants and TSPP.

Because of the reduced operating hours for fossil power plants, expensive fuels, and little flexibility of lignite and nuclear power plants, conventional power plants are no longer the cheapest option when generating electricity for the residual load. The solution of TSPP is cheaper because of using renewable primary energy sources, more flexible because of the integrated heat storage, and emission free. Driven by these factors, the cost of power generation from conventional power plants and TSPP needs to be calculated in detail in order to reflect the specific economic comparison between the two types of power plants, which is the purpose of this paper.

The paper at hand shows an LCOE-comparison of existing conventional thermal power plants and TSPP under German frame conditions. In the model analysis at hand, TSPP can be newly built, completely replacing existing plants, or obtained from a transformation of existing plants. The paper is organized as follows: chapter 2 presents a basic configuration and explains the cost composition of TSPP. Also, the cost difference between the newly built TSPP and a TSPP obtained from the conversion of a biomass power plant is discussed in this part, yielding a 100 % renewable version of a TSPP. Chapter 3 explains the source of the different model parameters and the underlying assumptions. Finally, chapter 4 summarizes the results of this calculation for different types of power plants. Chapter 5 presents a discussion about the influence of the CO_2 price as well as a sensitivity analysis of several model parameters. Conclusions and outlook for further work can be found in chapter 6.

2. Method

2.1. Configuration of TSPP and the difference between TSPP and conventional power plants

TSPP can be newly built or obtained from converting conventional thermal power plants. In this paper, four types of conventional power plant configurations will be discussed that have the potential to be converted to TSPP:

- Biomass power plant
- Coal fired power plant
- Gas turbine power plant

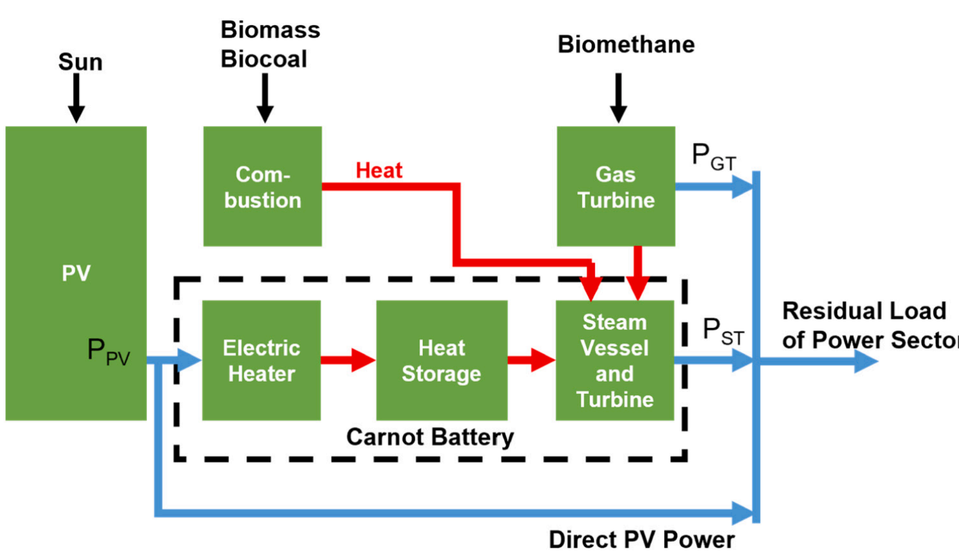

Fig. 1. Simplified schematic of a TSPP.

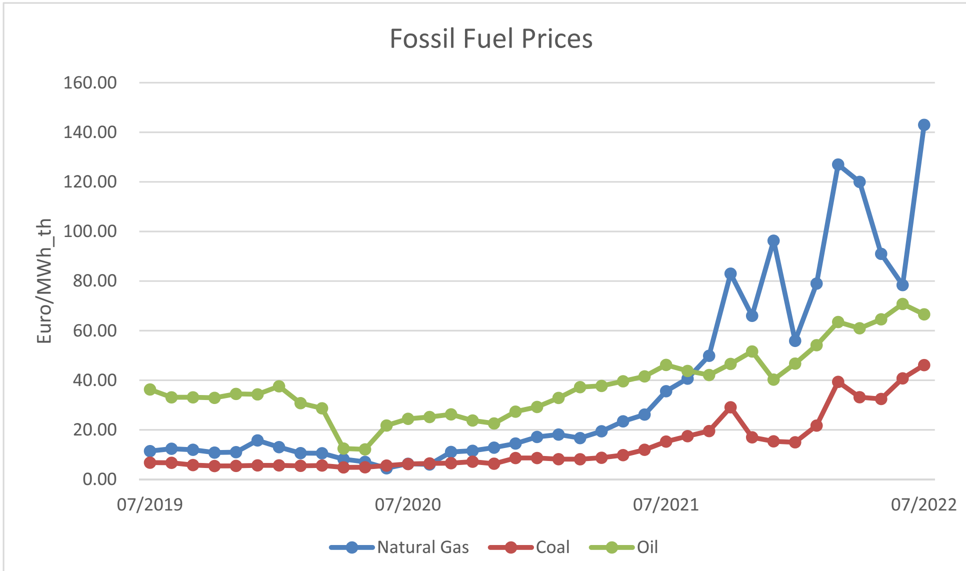

Fig. 2. Fossil fuel prices in the last 3 years (Euro per MWh_{th}) [6,12,13].

- Combined cycle power plant

An important difference between thermal storage power plants and conventional power plants is the additional PV field as primary energy input, the electric heater and the thermal storage unit to store electricity in form of heat. Fig. 3 shows the new components of TSPP after transformation, which should be newly constructed in case of transforming three types of fossil power plants: steam cycles, gas turbines and combined cycles. Thus, when considering transforming conventional power plants to TSPP, the following components should be newly built:

For steam turbine power plants (biomass, coal, lignite), the original main components (steam cycle, steam generator, turbine) will be considered as backup energy source. One option is to keep the original steam turbines and add all other equipment accordingly. In this case, the required PV plant, which is proportional to the size of the steam turbine, may become very large (a factor of 5 has been found useful under German conditions [1]). Another option is to replace part of the original steam turbine capacity by more flexible gas turbines. In this case a new, smaller steam cycle must be added. The photovoltaic plant is needed as primary energy source to reduce fuel consumption. A thermal storage unit, which consists of electric heater, thermal storage tank and storage steam generator is needed to absorb surplus PV-power and deliver it later on demand. A gas turbine and a heat recovery steam generator are optionally installed to cover loads that exceed the capacity of the steam turbine, if necessary.

Gas turbine power plants already include a gas turbine for TSPP. In this case, steam cycle components mentioned above are additionally needed to construct the backup part. The combined cycle power plants already have gas turbine and steam cycle components, so they only need the photovoltaic fields and the storage system for transformation. In this case, the combustion of biomass for steam generation is an additional option to reduce biomethane consumption. Table 1 shows the extra needed components for several types of fossil power plants while transforming to TSPP.

2.2. *Cost composition of conventional power plants and TSPP*

The method of cost comparison between the conventional power plants and TSPP is to calculate their LCOE (levelized cost of energy). The definition of LCOE can been seen below. The annual cost consists of four parts, which is capital cost, operation cost, fuel cost and CO_2 cost:

$$LCOE = \frac{Total\ Annual\ Cost}{Annual\ Electricity\ Generation} = \frac{C_{Capital,Annual} + C_{O\&M,Annual} + C_{Fuel,Annual} + C_{CO2,Annual}}{E_{Annual}} \tag{1}$$

Table 2 shows the parameters of the LCOE model used here. It is necessary to mention that all items are given in constant net present value in 2020.

The annual capital cost $C_{Capital,\ Annual}$ is the annual stationary cost related to the power plant investment in its entire life including capital payback and interest rate. Decision makers often use this parameter for capital budgeting decisions, as it allows them to compare the cost-effectiveness of various assets with unequal economic lives or discount rates [10]. $C_{Capital,\ Annual}$ is a function of total investment cost $C_{Invest,\ Total}$ and equivalent annual cost factor $A_{r,\ t}$, also called annuity.

$$C_{Capital,Annual} = C_{Invest,Total} \times A_{r,t} \tag{2}$$

The total investment cost consists of the EPC cost, EPC contracting fees and owner's costs. For conventional power plants, EPC costs include mechanical system costs, electric system costs, civil costs, and indirect costs. Mechanical system costs are mainly hardware costs of the power plant equipment, which consists of power equipment (turbine, generator, etc.), fuel conversion equipment (burner, boiler, etc.), and the balance of plant (fuel handling, treatment, auxiliaries, etc.) [11]. The electric system costs are the costs for power supply, such as substations and switchyards, main & aux power system, etc. [11]. Civil costs consist of the costs for civil, structural, and architectural work during the power plant construction, and the indirect costs relate to some expenses like transport costs, administration costs, office costs, utilities, etc. [11].

When transforming conventional power plants instead of constructing a new power plant, this leads to additional costs named "transformation costs" that are part of the EPC cost. Transformation costs represent the costs for removing the old unnecessary equipment, as well as other miscellaneous expenses arising from renovation. Eq. (2) can also be written as:

$$C_{Capital,Annual} = C_{Invest,Total} \times A_{r,t} = \left(C_{EPC} + C_{Fee} + C_{Owner} + C_{Transform}\right) \times A_{r,t} = \left(C_{Mech} + C_{Elec} + C_{Civil} + C_{Indirect} + C_{Transform} + C_{Fee} + C_{Owner}\right) \times A_{r,t} \tag{3}$$

$A_{r,\ t}$ is an equivalent annual cost factor, which is a function of discount rate and the power plant economic life assuming equal annual

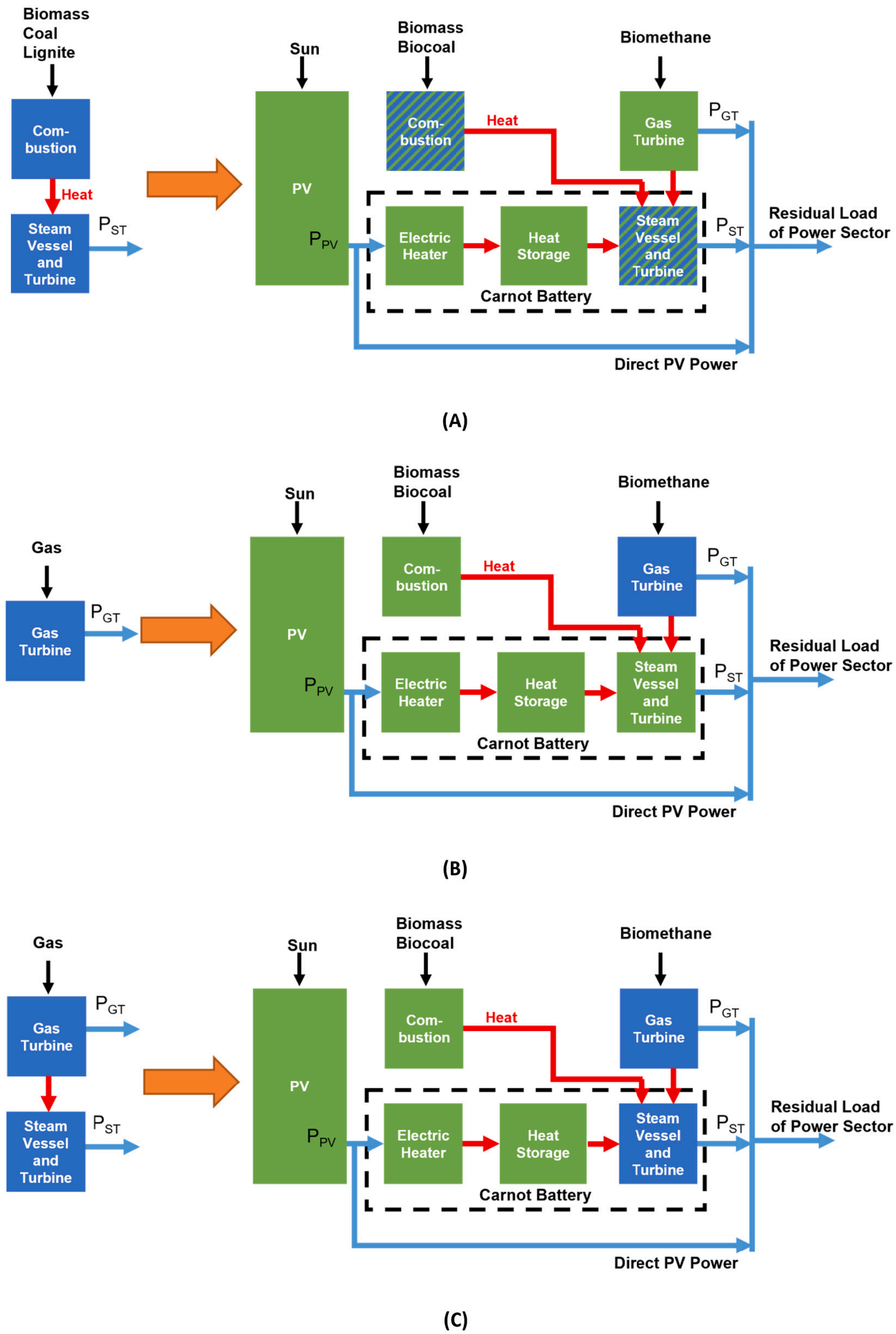

Fig. 3. Transformation of power plants to TSPP. Blue: original components of conventional power plants; Green: new components required for TSPP. A: steam cycle; B: gas turbine; C: combined cycle. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

payment rates: [10].

$$A_{r,t} = \frac{r}{1-(1+r)^{-t}} \tag{4}$$

The annual operation cost represents the ongoing expenses incurred from the normal day-to-day operation of the power plant, which consists of fix operation costs and variable operation costs. Fix operation costs mainly include the O&M labor costs, contracted maintenance services, materials, etc. It is calculated by a certain percentage of the total project investment. The variable operation costs include water treatment costs, wastewater treatment costs, fly ash and bottom ash disposal costs, etc. [11]. It is a function of the annual electricity generation E_{Annual} and the

Table 1
Additional components required for the transformation of conventional power plants to TSPP plants.

TSPP components	Steam turbine power plants	Gas turbine power plants	Combined cycle power plants
Steam Cycle	[b]	√	–
Gas Turbine	√	–	–
Photovoltaic Plant	√	√	√
Electric Heater	√	√	√
Thermal Energy Storage	√	√	√
Backup Heater	included in Steam Cycle	√	√
Backup Steam Generator[a]	included in Steam Cycle	√	√
Storage Steam Generator[a]	√	√	√
Heat Recovery Steam Generator[a]	√	√	–

[a] For optimal design, it might be favorable to integrate backup-, storage- and heat recovery steam generators in one single unit. However, in order to base the analysis on conservative cost estimates, separate units were assumed here.
[b] When transforming the steam turbine power plants to TSPP, a new steam turbine with a smaller capacity and complementing peaking gas turbines will be constructed in order to keep the overall capacity unchanged. This results in additional investment costs for the total steam cycle including backup burner and steam generator.

Table 2
List of model parameters.

$A_{r,\ t}$	Fix charge rate (Annuity)
r	Discount Rate (Net present value) (%)
t	Economic Life (a)
$C_{Capital,\ Annual}$	Equivalent annual capital cost (€/a)
$C_{Invest,\ Total}$	Total project investment (€)
$C_{O\&M,\ Annual}$	Annual operation cost (€/a)
$C_{O\&M,\ Fix,\ Annual}$	Annual fix operation cost (€/a)
$C_{O\&M,\ Variable,\ Annual}$	Annual variable operation cost (€/a)
$c_{Fix,\ spec}$	Specific annual fix operation cost (% of total project investment/a)
$c_{Variable,\ spec}$	Specific variable operation cost (€/MWh)
$C_{Fuel,\ Annual}$	Annual fuel cost (€/a)
c_{Fuel}	Fuel cost (€/MWh_{th})
$C_{CO2,\ Annual}$	Annual CO_2 cost (€/a)
c_{CO2}	CO_2 price (€/t)
C_{EPC}	Engineering, Procurement and Construction cost (€)
C_{Fee}	EPC contracting fees (€)
C_{Owner}	Owner's cost (€)
C_{Mech}	Mechanical system cost (€)
C_{Elec}	Electrical system cost (€)
$C_{Indirect}$	Indirect cost (€)
$C_{Transform}$	Transformation cost (€)
C_{Total}	Total Annual cost (€/a)
E_{Annual}	Annual electricity generation (MWh_e)
$M_{CO2,\ Annual}$	Annual CO_2 emissions (t/a)
$M_{Fuel,\ Annual}$	Annual fuel consumption (MWh_{th})
$m_{Spec,\ Fuel}$	Specific CO_2 emission fuel (t/MWh_{th})

specific variable cost factor $c_{Variable,\ spec}$ related to electricity generation.

$$C_{O\&M,Annual} = C_{O\&M,Fix,Annual} + C_{O\&M,Variable,Annual} = C_{Invest,Total} \times c_{Fix,spec} + E_{Annual} \times c_{Variable,spec} \tag{5}$$

Fuel costs consist of the average market price of the fuel and annual fuel consumption. It is worth mentioning that for TSPP there are multiple fuels for power generation (mostly biomass + biomethane), and both fuels have different prices and consumption. The total fuel costs are the sum of both.

$$C_{Fuel,Annual} = \sum_{i=1}^{n} \left(c_{Fuel,i} \times M_{Fuel,i}\right) \tag{6}$$

For fossil fuel power plants, the cost of carbon dioxide is a non-negligible part. The CO_2 cost consists of the annual CO_2 emissions and the CO_2 price according to the respective policy and market situation.

$$C_{CO2,Annual} = M_{CO2,Annual} \times c_{CO2} = \sum_{i=1}^{n} \left(m_{Spec,Fuel,i} \times M_{Fuel,i}\right) \times c_{CO2} \tag{7}$$

2.3. *Comparison of newly constructed TSPP and of TSPP obtained from transformation*

When talking about the transformation of conventional power plants to TSPP, there are two options for such transformation. One option is that the old conventional power plant will be completely shut down and decommissioned, and a TSPP with completely new equipment will be constructed with the same capacity in order to replace the former power plant. Another option is to keep the useful parts/equipment (boiler, etc.) as well as the supporting facilities (electric, etc.) of the old plant as far as possible, and only the additional equipment required for TSPP will be newly constructed in order to avoid unnecessary expenses.

In the case of new construction, all the mechanic and electric equipment must be paid for, as well as the civil costs, owner's costs, etc. The only cost that is not relevant in this case is the transformation cost.

$$C_{Transform} = 0 \tag{8}$$

In the case of transformation, according to the turbine type of conventional power plants, the components mentioned in Table 1 need to be paid for, and the cost of existing equipment will be saved. In addition, because of the already existing supporting facilities, other costs, such as electric system cost, EPC contracting fees and owner's costs will be saved:

$$C_{Elec} = 0 \tag{9}$$

$$C_{Fee} = 0 \tag{10}$$

$$C_{Owner} = 0 \tag{11}$$

However, as mentioned above, an additional cost for transformation will arise. In this paper, this parameter is set to a lump sum of 200 Euro per kW of power plant capacity.

$$C_{Transform} = 200\ €/kW \tag{12}$$

In case of transformation, the annual capital cost will be simplified to:

$$C_{Capital,Annual,TSPP} = \left(C_{Mech} + C_{Civil} + C_{Indirect} + C_{Transform}\right) \times A_{r,t} \tag{13}$$

3. Data and assumptions

Model parameters will be quantified in the following.

3.1. *Economic model parameters*

For conventional power plants, information sources are taken from a capital cost report made by US energy information administration (EIA). This report presents various types of real conventional power plants and their investment cost details. Table 3 shows the investment structure of a 50 MW biomass power plant [11]. Data from the EIA report is used in this paper in order to define reference values for comparison with TSPP.

For TSPP, a cost table in the same format was produced to make the comparison. The first step is to estimate the mechanical system cost of a TSPP from simplified extrapolation according to the plant's capacity. Scale effects are not taken into consideration:

$$C_{ST,TSPP} = C_{Mech,origional} \times \frac{P_{ST,TSPP}}{P_{ST,Original}} \text{ (Steam turbine power plants)} \tag{14}$$

Table 3
Investment cost structure according to EIA [11].

Mechanical Subtotal	Boiler Plant
	Turbine Plant
	Balance of Plant
Electrical Subtotal	Main and Auxiliary Power Systems
	BOP and I&C
	Substation and Switchyard
Civil/Structural/Architectural Subtotal	
Project indirect	
EPC Contracting Fee	
Owner's Cost Subtotal	
O&M Cost (annual)	Fixed O&M
	Variable O&M

$$C_{GT,TSPP} = C_{Mech,origional} \text{ (Gas turbine power plants)} \quad (15)$$

Other TSPP component prices are already determined: Table 4 illustrates the specific prices of the TSPP components according to Trieb et al. [1], including steam cycle, gas turbine, PV and heat storage.

The next step is to determine the electrical system cost of a TSPP. In this paper, the electric system cost of TSPP is assumed to be 30 % of the mechanical system cost.

$$C_{Elec,ST} = 30\% \times C_{ST,TSPP} \text{ (Steam turbine power plants)} \quad (16)$$

$$C_{Elec,GT} = 30\% \times C_{GT,TSPP} \text{ (Gas turbine power plants)} \quad (17)$$

Contrary to the data obtained for conventional plants, the specific prices for the TSPP components in Table 4 already include the electric system cost.

The fix and variable TSPP operation costs are calculated as follows:

$$c_{Fix,spec,TSPP} = 2\% \times C_{Invest,Total} \quad (18)$$

$$c_{Variable,spec} = 3 \frac{€}{MWh} \text{ (Reference Price)} \quad (19)$$

Fuel prices are another important economic factor. Table 5 summarizes the assumptions of the fuel prices for further calculation [6,12,13]. Because the fuel prices on spot markets may change significantly due to different reasons, in this paper the prices are set as much as possible to stay at the same level as the spot price in the year 2022 [6,12,13]. The last section of this paper includes a discussion about the relationship of LCOE and fuel prices, and the influence of fuel prices on total LCOE.

When it comes to environmental and economic impacts, the CO_2 costs related to different fuels cannot be ignored. From Table 6 it can be seen that coal and lignite cause higher CO_2 emissions per unit of lower heating value (LHV) compared to natural gas [14]. TSPP preferably use renewable fossil energy such as biomass and biomethane, which are CO_2 natural and free from paying extra CO_2 costs, and they will have advantage when compared to conventional power plants. The reference CO_2 price is assumed to be 55 Euro per ton.

$$c_{CO2} = 55\ €/t \text{ (Reference Price)} \quad (20)$$

Table 4
Specific investment costs of TSPP components [1].

Steam Cycle	€/kW	800
Gas Turbine	€/kW	550
Photovoltaic Plant	€/kW$_p$	600
Electric Heater	€/kW	100
Thermal Energy Storage	€/kWh$_{th}$	25
Backup Heater	€/kW$_{th}$	450
Backup Steam Generator	€/kW$_{th}$	100
Storage Steam Generator	€/kW$_{th}$	100
Heat Recovery Steam Generator	€/kW$_{th}$	100

Table 5
Assumed fuel costs [4–6].

Natural Gas (LHV)	€/MWh$_{th}$	100
Coal (LHV)	€/MWh$_{th}$	22
Lignite (LHV)	€/MWh$_{th}$	8
Biomass (LHV)	€/MWh$_{th}$	25
Biomethane (LHV)	€/MWh$_{th}$	75

Table 6
Specific CO_2 emissions of different fuels [14].

Natural Gas	t/MWh$_{th}$	0.2
Coal	t/MWh$_{th}$	0.34
Lignite	t/MWh$_{th}$	0.41
Biomass	t/MWh$_{th}$	0
Biomethane	t/MWh$_{th}$	0

3.2. Technical model parameters

The technical parameters of TSPP are also important for cost analysis. The total TSPP capacity consists of steam turbine capacity and gas turbine capacity. In this paper it is assumed that the steam turbine after transformation occupies about 30 % of the total capacity, and the gas turbine 70 % [1].

$$P_{TSPP} = P_{ST,TSPP} + P_{GT,TSPP} \quad (21)$$

$$P_{ST,TSPP} \approx 30\% \times P_{TSPP} \quad (22)$$

$$P_{GT,TSPP} \approx 70\% \times P_{TSPP} \quad (23)$$

For conventional steam turbine power plants, the capacity of the steam cycle will be downscaled to 30 % of the original size. In this case, the costs of the steam turbine from TSPP after transformation must be calculated again.

$$P_{ST,TSPP} \approx 30\% \times P_{ST,Original} \quad (24)$$

$$P_{GT,TSPP} \approx 70\% \times P_{ST,Original} \quad (25)$$

For gas turbine power plants, however, the original capacity will be conserved, and an additional new steam turbine equivalent to 30 % of the total capacity will be added.

$$P_{GT,TSPP} = P_{GT,Original} \quad (26)$$

$$P_{ST,TSPP} = 30\% \times \frac{P_{GT,TSPP}}{70\%} = 30\% \times \frac{P_{GT,Original}}{70\%} \quad (27)$$

For combined cycle power plants, the existing configuration regarding GT and ST (and the related equipment) will be conserved.

$$P_{ST,TSPP} = P_{ST,Original} \quad (28)$$

$$P_{GT,TSPP} = P_{GT,Original} \quad (29)$$

Another model parameter, the annual electricity yield of PV, is assumed to amount to 980 kWh/kWp per year.

Other parameters can be seen in Table 7 below. According to the model scenario by Trieb and Thess (2020), the annual full load hours of all plants are set to be 2700 h per year, as they are supposed to cover the future residual load of Germany [4].

4. Results: comparison of LCOE of conventional power plants and TSPP after transformation

4.1. Cost analysis: biomass power plant

In this case, a biomass-fired power plant with a capacity of 50 MW will be analyzed. It consists of a bubbling fluidized bed (BFB) boiler

Table 7
Reference capacities of conventional power plants and their technical parameters [1,11].

Fuel/plant type		Biomass	Coal	Gas	Combined cycle
Reference Capacity	MW	50	650	233	418
Efficiency Original Fuel LHV to Electricity	%	25.6[a]	40	34	53
Annual Full Load Hours (Residual Load)	h	2700	2700	2700	2700
Economic Life	a	35	40	50	40

[a] The low efficiency of the original biomass plant is caused by its use for combined heat and power.

which burns the wood chips, a single steam turbine and power generator.

In the case of transforming a biomass power plant to TSPP, an example from EIA with a capacity of 50 MW has been used [11].

Table 9 shows the annual fuel consumption of both power plants after calculation. According to the assumption that the annual full load hours to be covered by the plants amount to 2700 h per year, the plants should generate 135,000 MWh electricity per year. According to Table 7, the efficiency of the biomass power plant related to its fuel consumption is 38.3 %, which means that the consumption of solid biomass is 527,344 per year.

Because there are two types of fuels used by TSPP, the amounts of solid biomass and biomethane are calculated by the model used in Trieb et al. [1]. According to that, the conversion efficiency of biomethane to electricity of the TSPP has been found to be 57 %. That leads to about 70,000 MWh_{th} solid biomass and 129,000 MWh_{th} biomethane consumption per year, in order to generate the required amount of electricity. The high efficiency is achieved by the heat recovery steam generator (HRSG) that uses the gas turbine's waste heat for steam generation.

Thanks to the PV plant and heat storage, the TSPP consumes about 30 % less biomass energy than the original biomass plant and provides higher flexibility and added value. The capacity of both power plants is identical, which means that the capacity of the TSPP components can also be determined. The steam cycle makes up for 30 % of the total capacity (15 MW), while gas turbine capacity is set to 35 MW. Other parts of the TSPP are calculated according to [1].

As illustrated in Section 3.1, the investment of the TSPP steam cycle is calculated by downscaling the original biomass power plant:

$$C_{ST,TSPP} = C_{ST,origional} \times \frac{P_{ST,TSPP}}{P_{Total,Fossil}} = 88.8\ M€ \times \frac{15MW}{50MW} = 26.6\ M€ \tag{30}$$

Other components, such as gas turbine investment, are calculated by specific component price in Table 4. Table 10 shows the result regarding TSPP components.

$$C_{Others,TSPP} = c_{Spec,others} \times P_{Others} \tag{31}$$

Table 11 shows the LCOE calculation results of the biomass power plant and the TSPP. Column "Biomass Original" means the original biomass power plant that will be transformed, and component costs are taken from the EIA report [3]. The LCOE is about 195 €/MWh. The second column"New TSPP equivalent to biomass plant" illustrates the costs in case of constructing a new TSPP equivalent to the original biomass plant. As mentioned before, civil costs and indirect costs are already included in TSPP mechanical costs. In addition, no transformation cost is paid in this situation. The LCOE of a new TSPP is lower than that of a normal biomass power plant. More costs will be saved when conducting a conversion from a biomass power plant to a TSPP, since the electrical equipment is already installed and there's also no EPC- and owner's fee. Although there's an additional transformation cost, it's still worth it considering potential savings. The LCOE of the"-Biomass plant converted to TSPP" option is significantly lower than that of the original biomass power plant.

4.2. Cost analysis: coal fired power plant

One of the selling points of TSPP is to transform conventional fossil power plants in order to reduce their CO_2 emissions. In order to achieve this, there are basically two TSPP variations: new construction or conversion of the original plant. Table 12 below shows the four variations of TSPP for a coal fired power plant and their technical parameters [11].

The TSPP capacity of the coal fired power plant is also calculated by the same method as used for the biomass power plant. The steam turbine (195 MW) has been downscaled to 30 % of the original capacity, and a new gas turbine with 70 % of the total TSPP capacity (455 MW) is added.

Table 13 shows the TSPP component capacities as well as their prices for the two possible configurations. For TSPP using biomass and biomethane as additional energy source, the component price of the steam cycle is calculated from the steam cycle price in the original biomass power plant in Table 8:

$$C_{ST,TSPP} = C_{ST,Biomass} \times \frac{P_{ST,TSPP}}{P_{Total,Biomass}} = 88.8\ M€ \times \frac{195MW}{50MW} = 346.3\ M€ \tag{32}$$

Table 14 shows the LCOE calculation result of the coal power plant as well as the different TSPP configurations. The column "New TSPP equivalent to coal plant" refers to a newly constructed TSPP with biomass and biomethane as fuel. The result of these two configurations is that the "conversion" method saves more investment than new construction.

4.3. Cost analysis: natural gas fired gas turbine power plant

As shown before, when transforming gas turbine power plants to TSPP, there are basically two different configurations: one configuration is to downscale the current gas turbine to 70 % of the current capacity and add a steam cycle with 30 % of the original capacity; another configuration is to keep the current gas turbine unchanged and build an additional steam turbine with a capacity of 30 % of the new TSPP capacity. In this paper, the second configuration is determined to be the final TSPP capacity for gas turbine power plants.

Table 15 shows that the original capacity of the gas turbine is about 233 MW. Thus, the additional new steam turbine is calculated to be about 100 MW, and the total capacity of the TSPP is about 333 MW in total. Table 16 shows the component capacities and prices of this 333 MW TSPP. Note that because the capacity and the equipment of the gas turbine is unchanged, there is no extra cost for TSPP gas turbine:

$$C_{GT,TSPP} = 0 \tag{33}$$

Other components are calculated according to Table 4.

Table 17 shows the LCOE resulting for the original gas turbine power plant and for the new TSPP. Since it makes no sense to use natural gas as fuel of the steam turbine because biomethane is considered to be cheaper than natural gas, only one configuration will be discussed,

Table 8
Investment and operation cost of the original 50 MW biomass power plant according to EIA.

Investment cost		Original biomass plant
Mechanical Subtotal	M€	88.8
Electrical Subtotal	M€	26.6
Civil/Structural/Architectural Subtotal	M€	22.2
Project indirect	M€	15.4
EPC Contracting Fee	M€	15.3
Owner's Cost Subtotal	M€	22.9
Total Project Investment	M€	191.3
Operation cost		
O&M Cost (annual)	M€/a	6.7

Table 9
Technical comparison between original biomass power plant and TSPP [11].

Biomass		Original biomass plant	Biomass TSPP
Rated Power (MW)	MW	50	50
Efficiency Total Fuel LHV to Electricity[a]	%	25.6 %	68 %
Efficiency Solid Biomass LHV to Electricity	%	25.6 %	36.1 %
Efficiency Biomethane LHV to Electricity	%	–	57.0 %
Annual Electricity Generation	MWh/a	135,000	135,000
Annual Solid Biomass Consumption (LHV)	MWh_{th}/a	527,344	70,000
Annual Biomethane Consumption (LHV)	MWh_{th}/a	–	129,000

[a] This is the apparent efficiency (Total Power Output / Total Fuel Input) including fuel savings by PV and storage in case of TSPP. The net conversion efficiencies of biomass and biomethane (not including gains from PV and storage) are lower.

Table 10
Component costs of a 50 MW TSPP.

TSPP components layout	Spec. component cost	Component layout	Component cost
Steam Cycle	1776 €/kW	15.0 MW	26.6 M€ (Eq. 30)
Gas Turbine	550 €/kW	35.0 MW	19.2 M€
Photovoltaic Plant	600 €/kW	75.0 MW	45 M€
Electric Heater	100 €/kW	49.5 MW	4.9 M€
Thermal Energy Storage	25 €/kW_{th}	427.8 MWh_{th}	10.7 M€
Backup Heater (already included in steam cycle)	–	41.5 MW_{th}	(Already included in steam cycle cost)
Backup Steam Generator (already included in steam cycle)	–	35.3 MW_{th}	(Already included in steam cycle cost)
Storage Steam Generator	100 €/kW_{th}	35.6 MW_{th}	3.5 M€
Heat Recovery Steam Generator	100 €/kW_{th}	55.2 MW_{th}	5.5 M€
Total Mechanical system cost			115.6 M€
Electrical system cost			8 M€
Total			123.6 M€

which uses biomass and biomethane as primary energy sources. The result shows that due to the high price of the natural gas in the current market, the LOCE difference between the gas turbine power plant and the TSPP is significantly high. In this case, TSPP has considerable advantage.

4.4. Cost analysis: combined cycle power plant

For combined cycle power plants, steam turbine and the gas turbine already exist, therefore it is not necessary to adjust the capacity of steam cycle and the gas turbine. Table 18 shows a typical combined cycle power plant with a capacity of 418 MW [11]. The TSPP after transformation has the same capacity, which is shown in Table 19.

Table 20 illustrates the LCOE result of the original combined cycle power plant and its equivalent TSPP version.

5. Discussion

5.1. CO_2 avoidance costs

With the LCOE resulting from the original power plants and their TSPP variants, it is important to analyze the CO_2 avoidance cost of such transformation:

Table 11
LCOE calculation results of biomass power plant and TSPP [11].

		Biomass original	New TSPP equivalent to biomass plant	Biomass plant converted to TSPP
Mechanical Subtotal	M€	88.8	115.6	92.5
Electrical Subtotal	M€	26.6	8	0
Civil/Structural/ Architectural Subtotal	M€	22.2	Already included in steam cycle cost	Already included in steam cycle cost
Project indirect	M€	15.4	Already included in steam cycle cost	Already included in steam cycle cost
Transformation Cost	M€	–	0	10
EPC Contracting Fee	M€	15.3	12.3	0
Owner's Cost Subtotal	M€	22.9	18.5	0
Total Project Investment	M€	191.3	154.5	102.5
O&M Cost	M€/a	6.7	3.5	2.4
Capital Cost	M€/a	11.7	9.4	6.2
Fuel Cost	M€/a	13.2	11.4	11.4
CO_2 Cost	M€/a	0	0	0
Total Annual Cost	M€/a	31.6	24.5	20.3
LCOE	€/MWh	234	180	149

Table 12
Technical parameters of coal power plants and the resulting TSPP [11].

		Coal Conventional	New TSPP equivalent to coal plant	Coal plant converted to TSPP
Rated Power of Total Plant	MW	650	650	650
Efficiency Total Fuel LHV to Electricity[a]	%	40 %	67.8 %	67.8 %
Annual Full Load Hours (Residual Load)	h	2700	2700	2700
Annual Electricity Generation	MWh/a	1,755,000	1,755,000	1,755,000
Annual Coal Consumption (LHV)	MWh_{th}/a	4,387,500	–	–
Annual Solid Biomass Consumption	MWh_{th}/a	–	914,000	914,000
Annual Biomethane Consumption	MWh_{th}/a	–	1,671,000	1,671,000

[a] This is the apparent efficiency (Total Power Output / Total Fuel Input) including fuel savings by PV and storage in case of TSPP. The net conversion efficiencies of biomass and biomethane (not including gains from PV and storage) are lower according to Table 9.

$$C_{CO2,Avoidance} = Max\left\{0, \frac{C_{Total,TSPP} - C_{Total,Origional}}{M_{CO2,Annual,Origional} - M_{CO2,Annual,TSPP}}\right\} \quad (34)$$

The equation above describes the calculation of CO_2 avoidance costs. Note that in this paper, because the total investment and the CO_2 emissions of TSPP can be lower than that of the original power plant at the same time, the CO_2 avoidance costs can be negative. In order to avoid misunderstanding, all negative values are set to zero. TSPP can in fact reduce the LCOE and the CO_2 emissions at the same time.

Also, for the same reason, two types of CO_2 avoidance costs have been calculated: One are the costs including the CO_2 costs, and another

Table 13
Component costs of a 650 MW TSPP equivalent to original coal plant (using Biomass and Biomethane as fuel).

TSPP components layout	Spec. component cost	Component layout	New TSPP equivalent to coal plant	Coal plant converted to TSPP
Steam Cycle	-[a]	195.0 MW	346 M€	346 M€
Gas Turbine	550 €/kW	455.0 MW	250 M€	250 M€
Photovoltaic Plant	600 €/kW	975.0 MW	585 M€	585 M€
Electric Heater	100 €/kW	643.5.5 MW	64 M€	64 M€
Thermal Energy Storage	25 €/kW$_{th}$	5561.5 MWh$_{th}$	139 M€	139 M€
Backup Heater	-[a]	539.8 MW$_{th}$	-[a]	-[a]
Backup Steam Generator	-[a]	458.8 MW$_{th}$	-[a]	-[a]
Storage Steam Generator	100 €/kW$_{th}$	463.4 MW$_{th}$	46 M€	46 M€
Heat Recovery Steam Generator	100 €/kW$_{th}$	718.2 MW$_{th}$	71 M€	71 M€
Total			1503 M€	1503 M€

[a] Already included in steam cycle.

Table 14
LCOE calculation results of coal power plant and equivalent TSPP [11].

		Coal Original	New TSPP equivalent to coal plant	Coal plant converted to TSPP
Mechanical Subtotal	M€	1079	1503	1503
Electrical Subtotal	M€	160	103	0
Civil/Structural/ Architectural Subtotal	M€	235	-[a]	-[a]
Project indirect	M€	323	-[a]	-[a]
Transformation Cost	M€			130
EPC Contracting Fee	M€	179	161	0
Owner's Cost Subtotal	M€	413	369	0
Total Project Investment	M€	2392	2137	1633
O&M Cost	M€/a	34	28	23
Capital Cost	M€/a	139	124	95
Fuel Cost	M€/a	97	148	148
CO_2 Cost	M€/a	82	0	0
Total Annual Cost	M€/a	352	302	267
LCOE	€/MWh	201	171	152

[a] Already included in steam cycle.

one has excluded the CO_2 costs in order to lower the difference between the original power plants and TSPP. Concerning the fact that some countries in the world have not introduced CO_2 cost into consideration, this value is also of relevance.

Table 21 shows the results of CO_2 avoidance costs from the different types of TSPP in relation to their original power plants. When considering the CO_2 costs, all types of TSPP don't require any additional CO_2 avoidance costs, which means that TSPP have lower LCOE, and at the same time leads to lower CO2 emissions. In case of excluding CO_2 prices, most of the TSPP variants resulting from a transformation of old power plants also result in zero CO_2 avoidance costs.

5.2. Sensitivity analysis

This section describes the influence of different cost factors on the resulting LCOE. As mentioned above, the LCOE is calculated from several parameters, such as the fuel costs, component costs, discount rate, etc. Small changes in some of those parameters can lead to relatively strong changes in the final LCOE results, while others will only cause a small difference of the results.

Table 15
Technical parameters of gas turbine power plant and TSPP after conversion [11].

Fuel/plant type		Gas turbine	Gas turbine converted to TSPP (233 MW GT + 100 MW ST)
Rated Power of Total Plant (MW)	MW	233	333
Efficiency Total Fuel LHV to Electricity[a]	%	34.0 %	67.9 %
Efficiency Solid Biomass LHV to Electricity	%		36.1 %
Efficiency Biomethane LHV to Electricity	%		48.0 %
Annual Full Load Hours (Residual Load)	h	2700	2700
Annual Electricity Generation	MWh/a	629,100	898,714
Annual Natural Gas Consumption (LHV)	MWh$_{th}$/a	1,850,294	
Annual Solid Biomass Consumption (LHV)	MWh$_{th}$/a		469,000
Annual Biomethane Consumption (LHV)	MWh$_{th}$/a		855,000

[a] This is the apparent efficiency (Total Power Output / Total Fuel Input) including fuel savings by PV and storage in case of TSPP. The net conversion efficiencies of biomass and biomethane (not including gains from PV and storage) are lower according to Table 9.

Table 16
Component capacity and investment cost of a 333 MW TSPP [11].

TSPP Components Layout	Spec. Component Cost	Component Layout	Component Cost
Steam Cycle	800 €/kW	99.8 MW	79.8 M€
Gas Turbine	305 €/kW	233.0 MW	0 M€ (Original gas power plant)
Photovoltaic Plant	600 €/kW	499.3 MW	299.5 M€
Electric Heater	100 €/kW	329.5 MW	32.9 M€
Thermal Energy Storage	25 €/kWh$_{th}$	2848.0 MWh$_{th}$	71.2 M€
Backup Heater	450 €/kW$_{th}$	276 MW$_{th}$	124.3 M€
Backup Steam Generator	100 €/kW$_{th}$	234.9 MW$_{th}$	23.5 M€
Storage Steam Generator	100 €/kW$_{th}$	237.3 MW$_{th}$	23.7 M€
Heat Recovery Steam Generator	100 €/kW$_{th}$	594.1 MW$_{th}$	59.4 M€
Total			714.6 M€

Table 17
LOCE calculation results of gas turbine power plant and TSPP after conversion [11].

		Gas turbine	Gas Turbine converted to TSPP (233 MW GT + 100 MW ST)
Mechanical Subtotal	M€	71	714
Electrical Subtotal	M€	20	0
Civil/Structural/ Architectural Subtotal	M€	12	already included in gas turbine
Project indirect	M€	19	already included in gas turbine
Transformation Cost	M€	–	0
EPC Contracting Fee	M€	12	0
Owner's Cost Subtotal	M€	18	0
Total Project Investment	M€	153	781
O&M Cost	M€/a	2	11
Capital Cost	M€/a	8	43
Fuel Cost	M€/a	185	76
CO_2 Cost	M€/a	20	0
Total Annual Cost	M€/a	216	130
LCOE	€/MWh	343	144

Table 18
Technical parameters of combined cycle power plants and the TSPP [11].

		Combined cycle	Combined cycle converted to TSPP
Rated Power of Total Plant	MW	418	418
Efficiency Total Fuel LHV to Electricity[a]	%	53.0 %	67.3 %
Efficiency Solid Biomass LHV to Electricity	%		31.6 %
Efficiency Biomethane LHV to Electricity	%		50.0 %
Annual Full Load Hours (Residual Load)	h	2700	2700
Annual Electricity Generation	MWh/a	1,128,600	1,128,600
Annual Natural Gas Consumption (LHV)	MWh_{th}/a	2,129,433	
Annual Solid Biomass Consumption (LHV)	MWh_{th}/a		1,070,000
Annual Biomethane Consumption (LHV)	MWh_{th}/a		608,000

[a] This is the apparent efficiency (Total Power Output / Total Fuel Input) including fuel savings by PV and storage in case of TSPP. The net conversion efficiencies of biomass and biomethane are lower according to Table 9.

Table 19
Component capacity of a 418 MW TSPP.

TSPP components layout	Spec. component cost	Component layout	Component cost
Steam Cycle + Gas Turbine	–	418 MW	0 M€
Photovoltaic Plant	600 €/kW	627 MW	510 M€
Electric Heater	100 €/kW	413.8 MW	56.1 M€
Thermal Energy Storage	25 €/kWh_{th}	3576.5 MWh_{th}	121.2 M€
Backup Heater	450 €/kW_{th}	347.1 MW_{th}	211.8 M€
Backup Steam Generator	100 €/kW_{th}	295 MW_{th}	40.0 M€
Storage Steam Generator	100 €/kW_{th}	298 MW_{th}	40.4 M€
Heat Recovery Steam Generator	100 €/kW_{th}	672.4 MW_{th}	already included in “Steam Cycle + Gas Turbine”

Table 20
LOCE calculation results of combined cycle power plant and TSPP [11].

		Combined cycle original	Combined cycle converted to TSPP
Mechanical Subtotal of Power Plant	M€	203	979
Electrical Subtotal	M€	28	0
Civil/Structural/Architectural Subtotal	M€	31	Already included in mechanical subtotal
Project indirect	M€	80	Already included in mechanical subtotal
Transformation Cost	M€	–	84
EPC Contracting Fee	M€	34	0
Owner's Cost Subtotal	M€	75	0
Total Project Investment	M€	451	1063
O&M Cost	M€/a	9	18
Capital Cost	M€/a	26	62
Fuel Cost	M€/a	213	72
CO_2 Cost	M€/a	23	0
Total Annual Cost	M€/a	271	152
LCOE	€/MWh	241	135

In order to discover the impact from different parameters, these parameters will be converted into relative variables in this section. It is assumed that the original reference value of these parameters used in Section 4 will be set to factor 1. These relative variables will be changed to lower or higher values in order to figure out which variable will have more impact on the LCOE value.

Table 21
CO_2 avoidance costs of different TSPP relative to 100 % fossil fuel plants.

		CO_2 avoidance costs (with CO_2 Costs)	CO_2 avoidance costs (without CO_2 Costs)
		€/t_{CO2}	
Coal	New TSPP equivalent to coal plant	0	21.01
	Coal plant converted to TSPP	0	0
Gas Turbine	Gas Turbine converted to TSPP	0	0
Combined Cycle	Combined Cycle converted to TSPP	0	0

For example, in the case of biomass power plant, it is interesting to find out the impact of biomass price on the final LCOE value. The default price of biomass is 25 Euro/MWh_{th}, so this value will be considered as relative variation “1.0”. When we change this value to “2.0”, it means that the biomass price has been set to 50 Euro/MWh_{th}, and the LCOE result will be increased. The reason of making these changes is to find out which parameters are more sensitive for LCOE.

Fig. 4 shows the result of a sensitivity analysis of original biomass power plant. From this diagram, it is interesting to see that the biomass cost affects the LCOE more than the discount rate. When the relative variation of biomass cost varies from 0.2 to 3.2, the LCOE changes from 156 Euro to 449 Euro.

Fig. 5 shows the result of a sensitivity analysis of the TSPP derived from this biomass power plant. In contrast to the original biomass plant, because TSPP consume much fewer biomass, the LCOE changes only

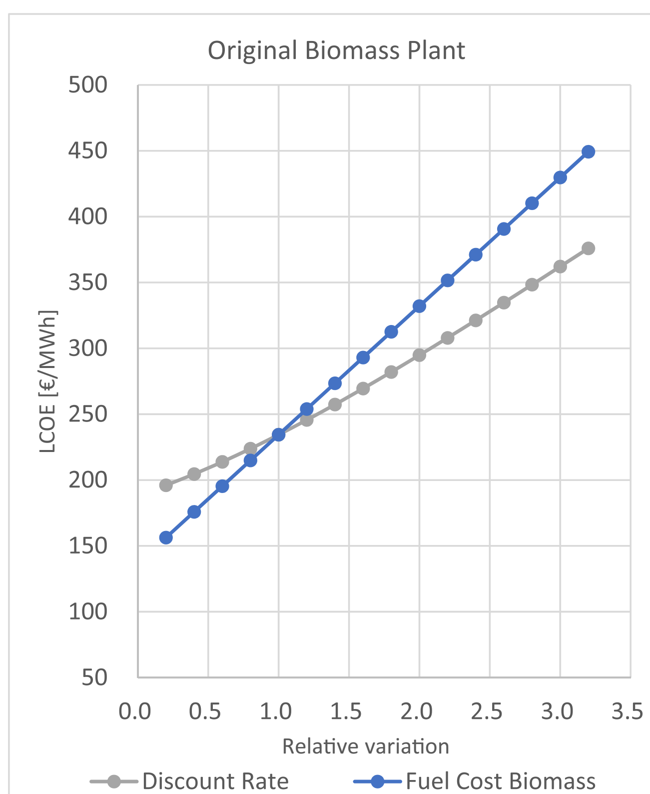

Fig. 4. Sensitivity analysis of original biomass power plant.

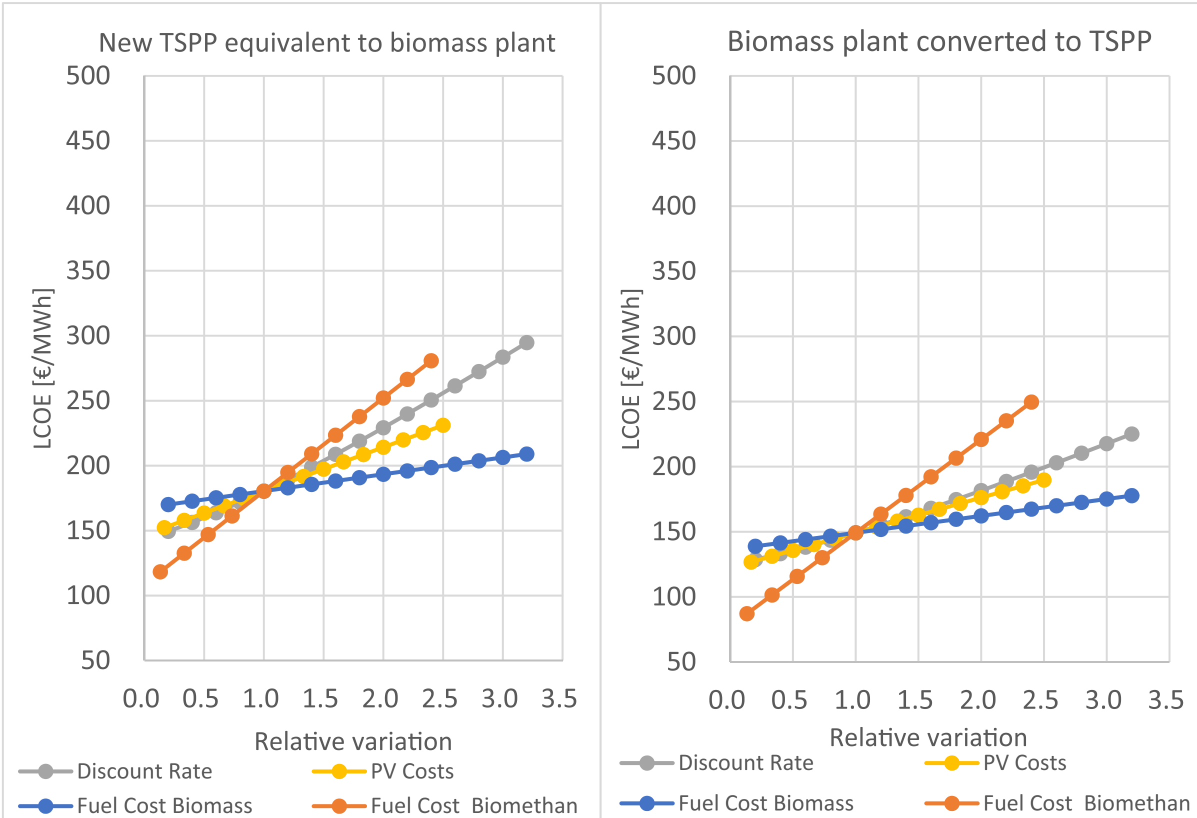

Fig. 5. Sensitivity analysis of TSPP power plant replacing a biomass power plant.

from 170 Euro to 208 Euro. The price of biomethane has the strongest influence on the LCOE. Also, from these two diagrams it can be seen that the LCOE of TSPP "conversion" is always lower than that of newly constructed TSPP, mainly because of lower capital costs. The influence of the discount rate is reduced in case of the "conversion".

When it comes to coal power plants, another parameter which is also worth analyzing is the CO_2 price. Fig. 6 shows the result of sensitivity analysis of original coal power plant. The CO_2 price affects the LCOE to a slightly lesser extent than the coal price and the discount rate, but all three parameters have a significant impact.

Converting the coal power plants to TSPP has significantly weakened the impact of fuel prices as well as the impact of the CO_2 price on LCOE (Fig. 7). Large fluctuations in coal prices will no longer significantly affect the normal operation of a power plant. At the same time, when TSPP completely abandoned coal in favor of biomass, the CO_2 price will no longer be one of the factors to be considered.

The changes before and after the conversion of gas turbine power plant as well as the combined cycle power plants are the most obvious. Fig. 8 and Fig. 9 have shown the sensitivity analysis of gas power plant and combined cycle power plant and their TSPP. Because of the high price of natural gas, the LCOE of the gas turbine power plant changes significantly even though the gas price has only been shifted slightly. In contrast to these power plants, the LCOE of TSPP is relatively stable, since TSPP consume biomethane, which does not change dramatically, being a local product. This makes TSPP a cost-effective alternative in the current energy market.

In the past, in the eyes of the public as well as decision makers, the usage of renewable energy and cost savings seemed to be two factors that could not be reconciled. However, from the calculation of CO_2 avoidance costs, it can be seen that TSPP can, in most cases, significantly reduce the utilization of fossil fuels and related carbon emissions while incurring no additional costs. This advantage of TSPP will become increasingly evident as the price of CO_2-emissions continues to rise in

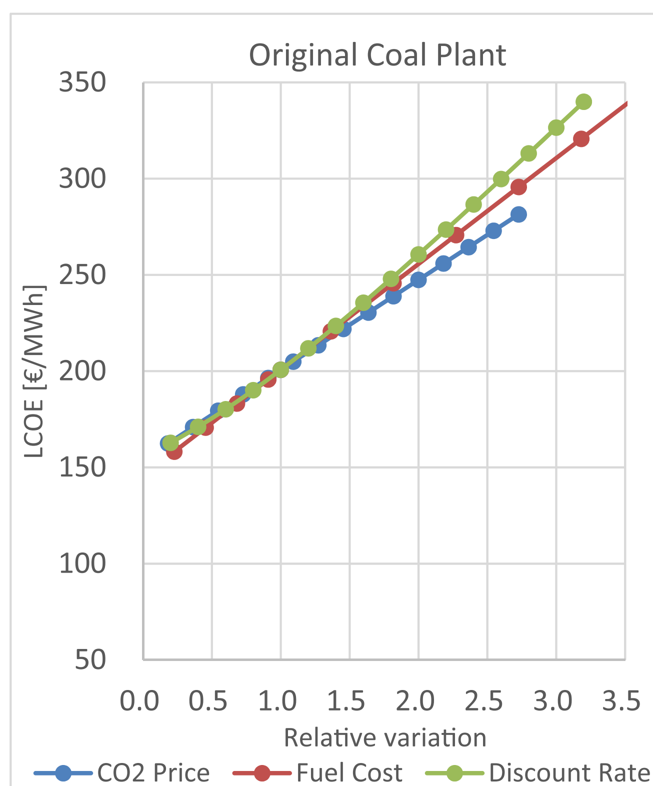

Fig. 6. Sensitivity analysis of original coal power plant.

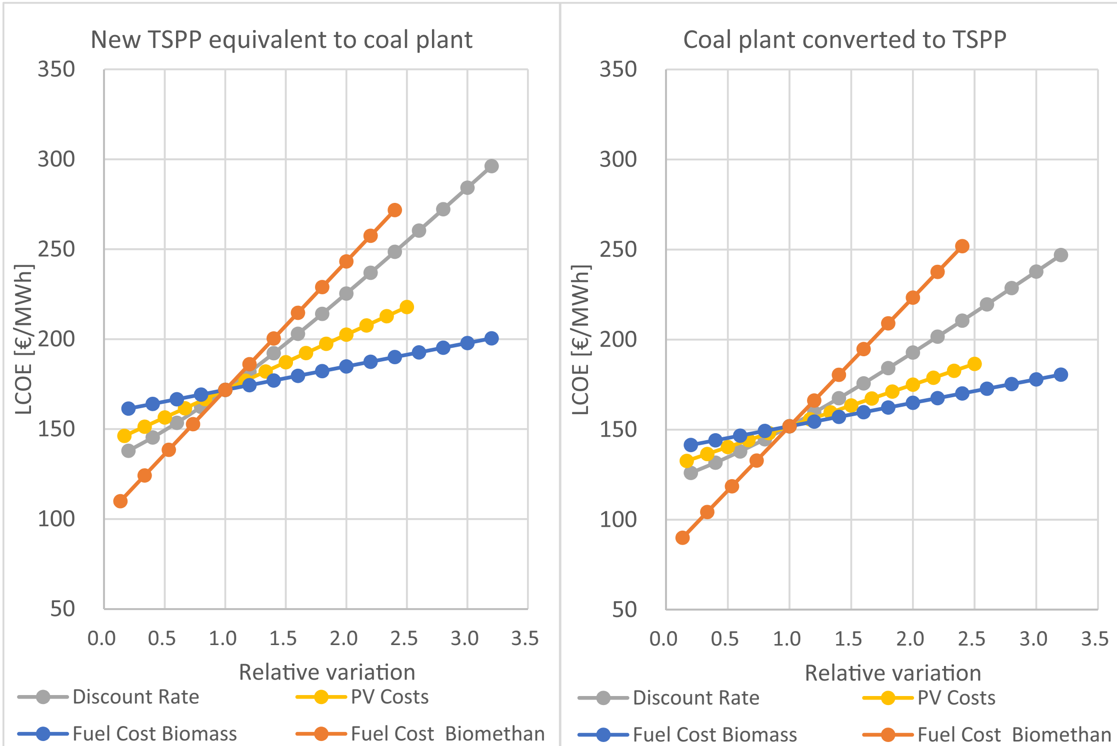

Fig. 7. Sensitivity analysis of TSPP power plant replacing a coal power plant.

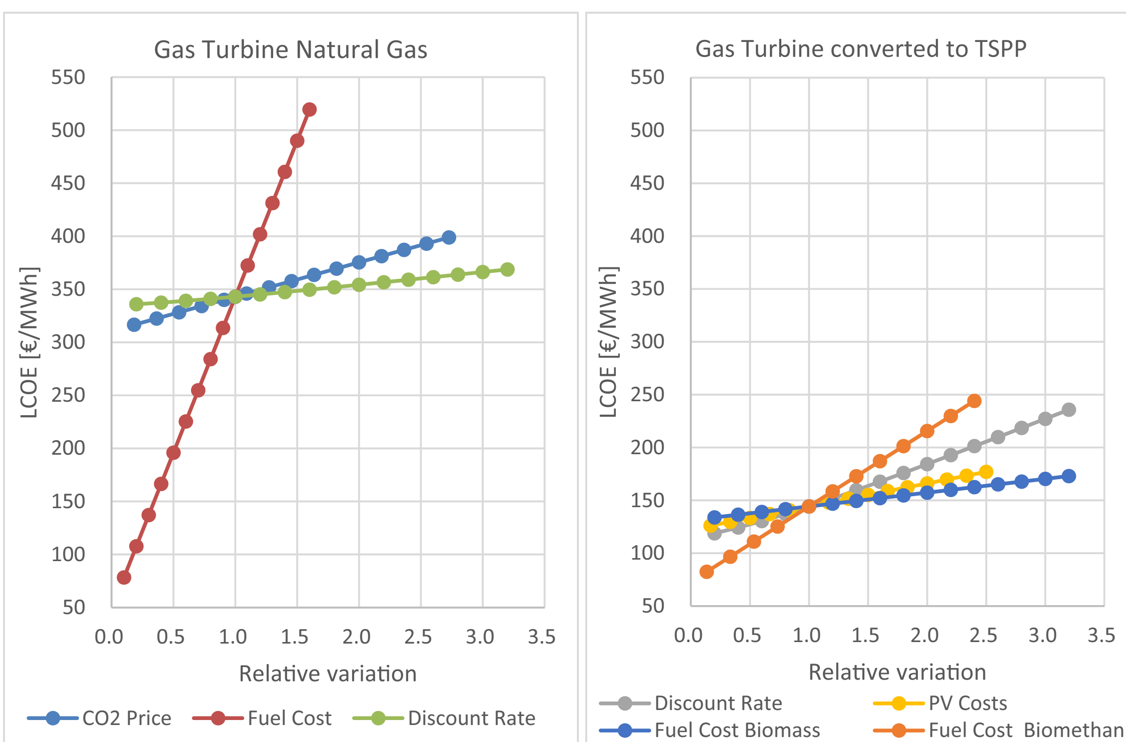

Fig. 8. Sensitivity analysis of gas power plant and TSPP power plant after conversion.

the future.

In addition, the sensitivity analysis in chapter 5.2 shows that TSPP can be applied as hedge against fuel- and CO_2 price escalation. TSPP's reduced usage or complete replacement of traditional fossil energy sources can significantly reduce the power plant's LCOE while at the same time also significantly increase the economic stability of the plant's operation. When the cost of fossil fuels fluctuates dramatically, it often exceeds the revenue of conventional power plants, causing them to shut down.

TSPP, on the other hand, can reduce the consumption of fossil energy

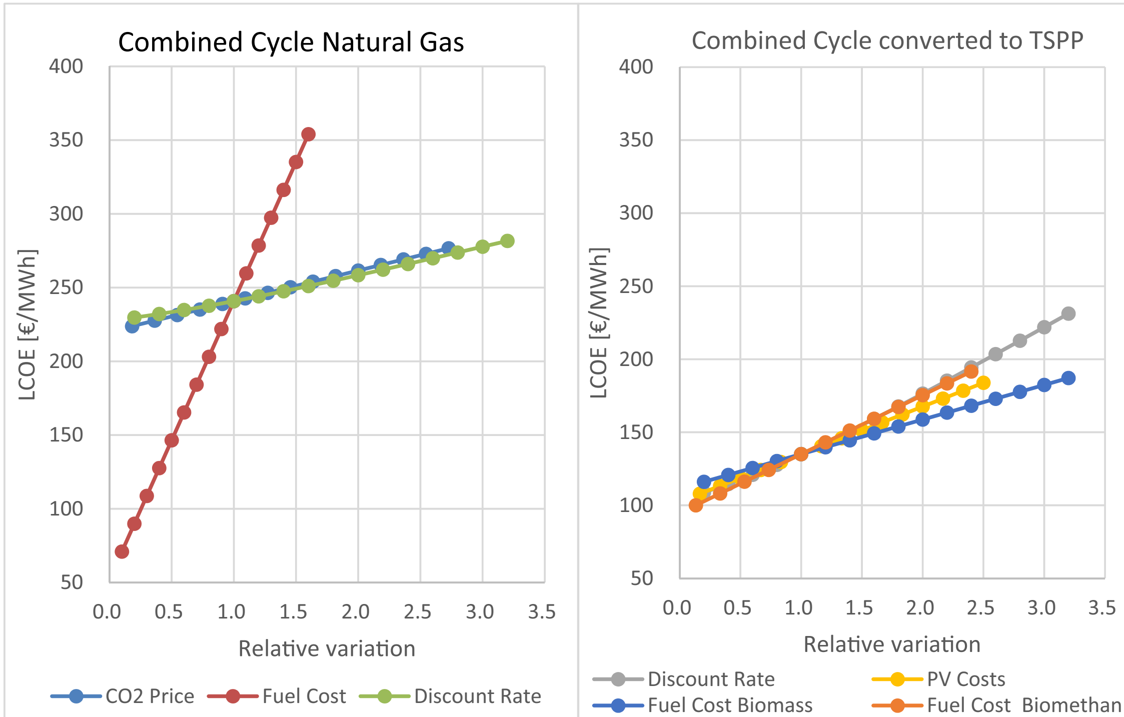

Fig. 9. Sensitivity analysis of combined cycle power plant and TSPP power plant after conversion.

sources by prioritizing the use of renewable energy with relatively stable prices, making their LCOE insensitive to sharp price fluctuations. It is also for this reason that TSPP also maintain a stable LCOE against CO_2 price variations. In today's energy situation, TSPP can be considered as insurance against rising world market fuel prices.

6. Conclusion and outlook

The purpose of this paper is to compare the levelized cost of electricity of different conventional power plants and equivalent TSPP power plants, in order to find out if TSPP are economically competitive in spite of additional investment and potential transformation cost.

After comparing the LCOE of four conventional power plants to their equivalent TSPP obtained from transformation, it results that TSPP have several advantages:

Unlike traditional fossil power plants running at base load without any flexibility, the TSPP can fulfill the demand of residual loads, providing a much higher flexibility thanks to the heat storage system, also called Carnot Battery. Thanks to a large PV plant integrated to the TSPP as primary energy source, the fuel consumption of a TSPP is considerably reduced and the apparent efficiency of converting fuel to electricity is particularly high.

Due to reduced usage of fossil fuels, TSPP satisfy the goal of reducing greenhouse gas emissions in the current world, especially when using biomass as backup fuel. TSPP cause no CO_2 avoidance costs or in some cases even allow for cost savings compared to conventional power plants.

The LCOE of TSPP is less sensitive to fuel price escalations than the LCOE of traditional power plants when facing the changes of the different variables, especially with respect to the dramatic changes of fuel prices this year. Mainly depending on local solar- and bioenergy sources, TSPP represent an effective hedge against fossil fuel price escalation as well as CO_2 cost additions on the world market.

TSPPs are theoretically cheaper than other options of providing flexible power for the residual load. As next step, this result must be proven by constructing first TSPP pilot plants.

In future research, it is planned to apply the calculation of LCOE to the power plants in a certain area as a ranking criterion for possible transformation to TSPP, together with other ranking criteria, which can help decision makers to determine which power plants are more worthy of being transformed or reconstructed [15,16].

CRediT authorship contribution statement

Pai Liu: Methodology, Software, Formal analysis, Investigation, Writing – original draft. **Franz Trieb:** Conceptualization, Methodology, Validation, Supervision, Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Data availability

Data will be made available on request.

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Paper III: Assessment of TSPP-Atlas in Germany

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The contribution of this paper is described as follows:

Pai Liu: Methodology, Software, Formal analysis, Investigation, Writing - Original Draft

Franz Trieb: Conceptualization, Methodology, Validation, Supervision, Writing - Review & Editing.

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Research papers

German atlas of Thermal Storage Power Plants (TSPP) - A first approach

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ABSTRACT

The paper assesses the potential of transforming conventional power plants to Thermal Storage Power Plants (TSPP) in Germany on a macro scale. The resulting atlas is based on a scenario of the power sector published before that assumes that current conventional power plants will be transformed to TSPP with a capacity of 70 GW in 2040, providing reliable power supply for the residual load. In order to achieve this, several criteria are introduced that rank all power plants in Germany in terms of suitability for such conversion. Moreover, a method of finding the necessary land areas for PV and biomass required as primary energy sources for the TSPP is described with the help of a geographic information system. The analysis is divided into 2 parts: The first part is to consider the whole country as a single entity, and all power plants are analyzed according to their ranking list in order to find out if the scenario is consistent with existing PV and biomass potentials. The second part focuses on individual power plants without considering the ranking list, in order to find the best potential PV and biomass supply areas for each potential power plant that could be transformed on a first-come-first-save basis. The findings of this study include mapping of the transformation potential of individual power plants, and also provides an integrated framework for a TSPP transition at the national level. By providing a comprehensive overview of the TSPP-atlas across the country, these maps may serve as a helpful tool for policymakers and power plant owners in making decisions regarding the deployment of TSPP.

1. Introduction

1.1. Background and motivation

Over the past decades, the cost of variable renewable electricity generation, including photovoltaic and wind power, has decreased significantly. Consequently, many countries have been replacing conventional power plants by renewable sources to meet their carbon reduction targets. However, as the share of renewable power generation increases, a new issue has emerged, known as residual load paradigm. In the second phase of the energy transition, strongly variable residual loads, particularly caused by the variability of renewable energy sources, will become a challenge for the energy security of some nations [1].

Another aspect that indicates the problem of current power supply structures is the fuel prices for the conventional power plants. In the long term, global energy demand is continuously increasing due to economic development, resulting in a gradual rise in energy prices. In the short term, especially in the past year 2022, the fuel prices, especially the natural gas price has risen and dropped significantly. Fig. 1 shows the natural gas price in Germany in the past 3 years [2,3]. As can be seen in this figure, in July 2022 the natural gas price has risen to its peak at >300 Euro/MWh$_{th}$, then it rapidly dropped in just 2 months to <50 Euro/MWh$_{th}$. In order to mitigate the impact of price fluctuations on the normal operation of power plants, many plants choose to partially alleviate the problem through hedging. However, this method also needs to consider additional costs and balance them with the additional revenues incurred by the hedging activities [4]. Hence, large fluctuations of the fuel prices can still affect the normal operation of conventional power plants.

It is also worth mentioning that most of conventional power plants, especially lignite and coal-fired power plants, are so called base-load power plants, with relatively inflexible power supply. They are not suited to follow fast load changes and cannot reduce their power capacity below a certain limit without shutting down completely [5]. A solution is needed that replaces these base load power plants, and at the same time supplies highly flexible power to the grid.

Moreover, in the future, the concept of base load won't be essential since the base load power plants such as coal fired power plants or

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nuclear power plants have been or will be shut down in the next few years in the case of Germany. Demand will certainly become more variable in the future.

The cost related to CO_2 emissions has been another burden to power plant operators. Fig. 2 illustrates the carbon trading price history in the European Union since 2008 [6]. In the past 10 years, this trading price has rapidly increased from <10 Euro/tCO_2 to >100 Euro/tCO_2, and it will probably continue to grow in the future. Therefore, providing a resilient energy supply and reducing the additional costs associated with carbon emissions has become a new direction for energy transition.

1.2. Energy scenario for Germany in 2040

Under the Paris climate protection agreement, Germany, like all other countries, has a duty to rid its energy system of greenhouse gases ("decarbonization"). According to the energy policy, Germany will orderly withdraw from the climate-damaging generation of electricity from lignite and hard coal by 2040 [7].

In 2020, Trieb and Thess have proposed a scenario for Germany for the year 2040 with the installation of TSPP [8]. Table 1 shows the capacity changes of different types of power plants in the following 20 years. According to their scenario, most of the fossil power plants, such as coal, nuclear and lignite, will be shut down. Instead, more PV and wind turbines will be installed, and TSPP will also be either newly constructed or obtained from repurposing existing power plants. The TSPP will consist of 21 GW steam turbines powered with solid biofuels like wood or straw pellets, 105 GW PV capacity integrated to the TSPP as primary energy source in order to save biofuel as much as possible, a 600 GWh_{th} heat storage with electric heater to absorb and reuse power surplus from the PV plant and from the grid, and 49 GW gas turbines with heat recovery steam generator in charge of covering peak loads that exceed the steam turbine's maximum capacity (Table 1).

With this scenario, according to the calculation from Trieb and Thess, TSPP would produce about 213 TWh per year in 2040 in order to cover the residual load, which equals about one third of total German electricity demand.

Table 2 illustrates the energy contribution of the different TSPP components. According to the calculations, these power plants would require approximately 1575 km^2 of land in Germany for the construction of photovoltaic panels. Additionally, each year, these TSPPs would consume approximately 141 TWh_{th} of biomass and 176 TWh_{th} of natural gas.

After these theoretical calculations, the next step is to validate the specific feasibility of this scenario. Firstly, in the aspect of photovoltaic, it is necessary to confirm whether there is sufficient available land near the transformed power plants for the installation of the required photovoltaic panels. This aspect has already been verified in a previous paper [9]. The main focus of the paper at hand is to consider the biomass aspect, specifically whether Germany has sufficient biomass potential to provide thermal energy for these TSPPs, and how to allocate the biomass resources to the nearby power plants that are most suitable for the transformation.

After confirming the feasibility of these two aspects, the final outcome will be a comprehensive atlas compilation for the transformation of thermal power plants to TSPPs in Germany. It will provide a complete solution, including the thermal power plants that will undergo this transformation, their specific geographical locations, and their physical characteristics. It will also include the geographic locations of the photovoltaic installations and the required biomass sources after transformation. With this TSPP atlas, future decision-makers will have at hand a specific solution for energy transition. Furthermore, it will serve as reference for specific transformation projects in the future, providing a pre-selection and pre-design of individual conventional power plants for transformation to TSPP.

2. Method

2.1. Configuration of TSPP and the difference between TSPP and conventional power plants

Fig. 3 shows a basic schematic of a TSPP [10]. It uses PV electricity as primary energy source, and it consumes biomass, such as bio-coal and biomethane as back-up fuel. A typical component of a TSPP is a thermal energy storage system named Carnot Battery, which uses molten salt to transform the electricity to heat in order to store energy for typically 12 h of full load operation per day. In this paper, the components like electric heater and the molten salt heat storage are used being state of the art technologies. In the future, new technologies can be applied on TSPP, such as a high temperature heat pump to replace the electric heater [11], and an ultra-high temperature heat storage to replace the molten salt heat storage [12].

TSPP can be obtained either by transforming conventional power plants to save on capital costs or by constructing new plants in locations with good availability of biomass resources and suitable photovoltaic (PV) plant locations. A detailed cost analysis as well as a comparison of TSPP and conventional power plants are discussed in [10,13].

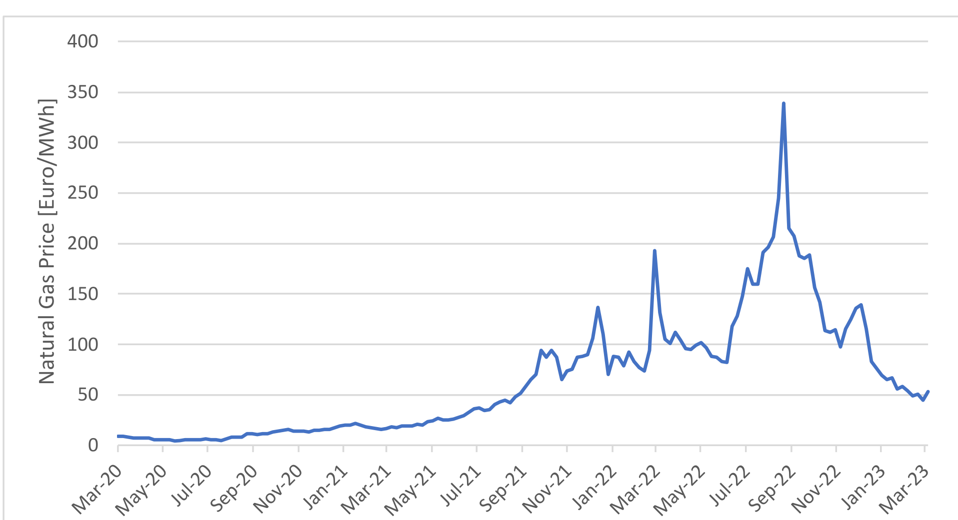

Fig. 1. Natural gas price in EU from Mar.2020 to Mar.2023, Euro/MWh [2,3].

Fig. 2. EU Carbon trading price history data from EU-ETS [6].

Table 1
Transformation of the power sector in the next 20 years according to the reference scenario by [8].

Model Year	2020	2030	2040
Renewable Capacity (MW)			
Photovoltaic	48,500	105,000	135,000
Wind Onshore	56,500	70,000	75,000
Wind Offshore	8400	12,500	14,000
Hydropower	5700	5640	5640
Solid Biomass, Wood, Waste	3000	1800	0
Biogas, Energy Crops	4700	0	0
Geothermal Power	38	250	1000
Hydropower Imports	0	250	1000
Thermal Storage Power Plant Capacity (MW)			
TSPP Photovoltaic	0	52,500	105,000
TSPP Steam Turbines	0	10,500	21,000
TSPP Gas Turbines	0	24,500	49,000
Fossil Power Capacity (MW)			
Gas Turbines	1390	17,200	19,300
Hard Coal Power Plants	22,000	14,500	0
Combined Cycles and Combined Heat and	28,700	15,500	0
Power	5700	0	0
Other	9400	0	0
Nuclear Plants	21,200	7000	0
Lignite Plants			
Storage and Grid Capacity (MW)			
Pump Storage	9850	9850	9850
Net Transfer Capacity Import	27,000	27,000	27,000
Net Transfer Capacity Export	23,000	23,000	23,000

2.2. *Economic TSPP model*

It is widely recognized that economic analysis plays a crucial role in determining the practical application and viability of new technologies. Table 3 presents a cost comparison between TSPP and conventional power plants, such as coal-fired steam power plants, gas turbine power plants and combined cycle power plants [10]. The results show that TSPP are economically competitive, although they have higher capital costs and additional transformation costs. At the same time, the LCOE of TSPP is less sensitive to the fluctuations of world-market fuel prices because of using domestic biomass and solar power as primary energy sources.

2.3. *Establishing a ranking list of fossil power plants in Germany for transformation to TSPP*

In a first approach, four criteria were considered for ranking existing power plant units:

- Operating years (age)
- The original power plant capacity.
- The life steam temperature of the Rankine cycle.
- The fuel type of the power plant

Table 4 shows the updated four ranking criteria for the power plants. A detailed explanation of the ranking criteria is given in [9]. After several iterations of the analysis, and consulting some experts, the following updates are made to these criteria:

Table 2
TSPP contribution to electricity supply for the residual load [8].

Component	Electricity
Total PV production from TSPP	102 TWh_{el}/a
PV supplied directly to consumers.	**45 TWh_{el}/a**
Power from steam turbine	**103 TWh_{el}/a**
PV supplied through heat storage,	22 TWh_{el}/a
through biomass back-up heat,	51 TWh_{el}/a, consuming 141 TWh_{th} of solid biomass
through HRSG.	30 TWh_{el}/a
Power from gas turbines	**65 TWh_{el}/a, consuming 176 TWh_{th}/a of natural gas**
TSPP total contribution 2040	**213 TWh_{el}/a (= residual load, 35 % of power demand)**

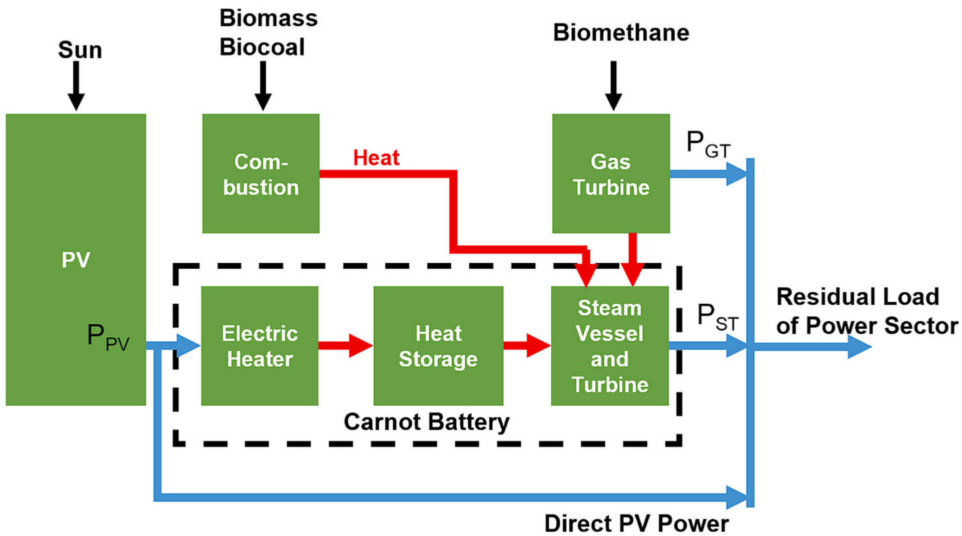

Fig. 3. Simplified schematic of a TSPP [10].

Table 3
LCOE result of some example power plants and corresponding TSPP after transformation [10].

LCOE [Euro/MWh]	Original power plant	TSPP
Combined Cycle natural gas	241	135
Gas turbine natural gas	343	144
Coal steam cycle	201	152
Biomass steam cycle	234	149

- Power plant capacity: The scoring of the power plant capacity is refined. It is decided that giving higher priority to power plants with a smaller capacity is a good option for transforming them into TSPP, because in this way less PV areas and bioenergy are needed per power plant, which is more realistic. Also, smaller and decentralized power plants are the potential new trend of energy transition. Giving priority to small over very large power plants is in line with this trend.
- Steam temperature of the Rankine cycle: The critical temperature of the molten salt determines the maximum steam cycle temperature, which is 565 °C. Solid state storage technologies are needed if life steam temperature is above this limit, which are still under development [14].

The other two ranking criteria remain unchanged:

- In terms of power plant operating time, we rate the lifespan of power plants based on a 20-year standard. Power plants with <20 years of operating time are considered relatively young and have the highest potential for transformation. Power plants with an operating time between 20 and 40 years are deemed to have moderate value. Power plants with an operating time exceeding 40 years are evaluated lower due to the aging equipment, and the economic feasibility of total demolition and reconstruction needs to be considered.
- Regarding the fuel used by conventional power plants, biomass power plants are considered as the most promising candidates for transformation due to their existing biomass handling equipment and the availability of supporting biomass supply chains. TSPP using biofuel can in fact be understood as highly flexible and highly efficient biomass power plants with extremely low heat rate. Other types of power plants are given a lower priority in terms of transformation potential.

2.4. *PV Atlas for TSPP in Germany*

In a first approach of the PV atlas for TSPP [9], the potential area of PV panels was determined by the following characteristics:

- Potential suitable land areas from global land cover database: Cultivated Land, grassland, shrubland and bare land. [15]
- Unsuitable land areas from World Topographic Map, Global Lakes and Wetlands Database, Global Roads Open Access Data Set, World Database on Protected Areas. [16–19]

After eliminating unsuitable land areas, the initial iteration of potential areas for photovoltaic (PV) installation in Germany, including agricultural land for Agri-PV, was identified. The selected areas are illustrated in Fig. 4, highlighted in blue.

In the course of the analysis at hand, this potential area was considered as too optimistic. On one hand, this PV potential area is much larger than what is actually needed by the TSPP. On the other hand, even if Agri-PV is introduced and installed, it still cannot be easily installed on any agricultural land in practical applications. Therefore, this potential area has been reduced as described in the following so that it can be more in line with practical applications.

In practical applications in Germany, PV installations are commonly installed alongside highways. Therefore, the following method is proposed to incorporate this feature in the analysis: As depicted in Fig. 4,

Table 4
Updated ranking criteria of the power plants in Germany for a transformation to TSPP used here.

Power Plant Properties	Score			
	①	②	③	④
Age	<20 y	20–40 y	>40 y	–
Power Plant Capacity	<100 MW	100–250 MW	250–500 MW	>500 MW
Steam Temperature	≤565 °C	>565 °C	–	–
Fuel	Biomass	Fossil fuels	–	

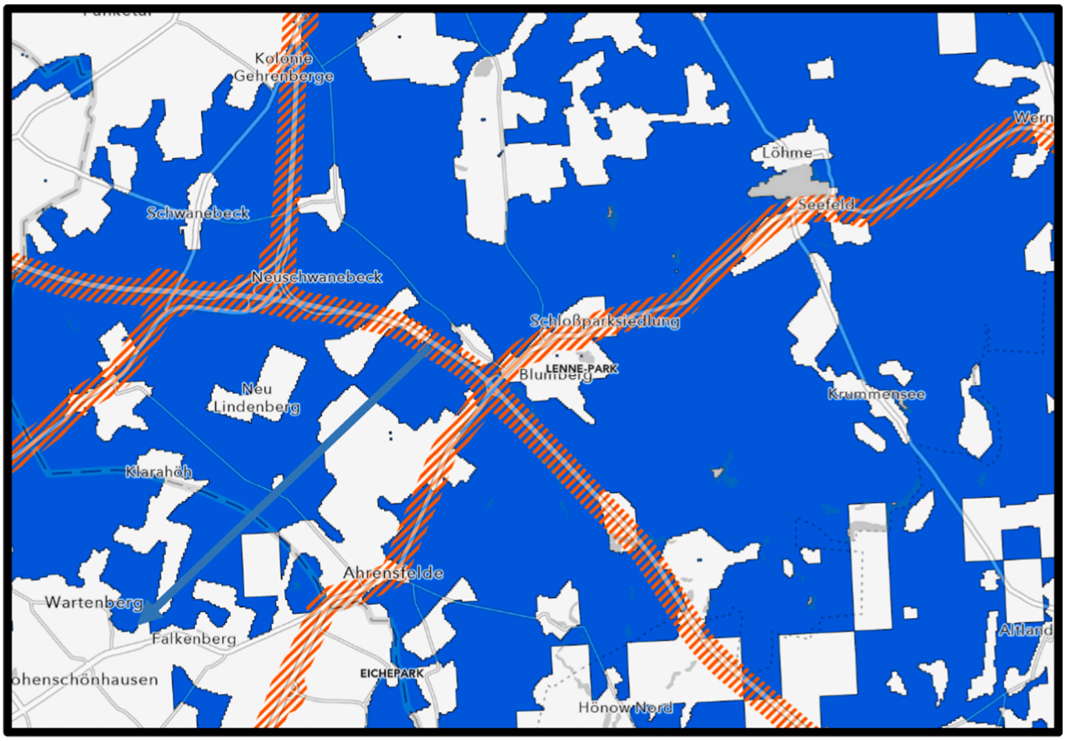

Fig. 4. Method of finding potential PV installation area for TSPP. Blue: PV potential area from [9]. Red (Dashed): The area within 200 m of the perimeter of the main roads in Germany. The overlapping area of these two attributes will be used as the potential area for the analysis at hand. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Potential PV installation area including Agri-PV alongside main roads. (Marked as blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the main highways in Germany are chosen to install PV along sides. At the same time, a potential area within 200 m on both sides of the road (marked as dashed red areas) is considered as the PV potential area for the subsequent iteration of the analysis. The overlap between the initial blue area and the red area will be the potential area of the PV installation, which is displayed in blue in Fig. 5.

Fig. 6 illustrates the enlarged view of the potential PV areas in Germany. The proposed method results in a total theoretical potential

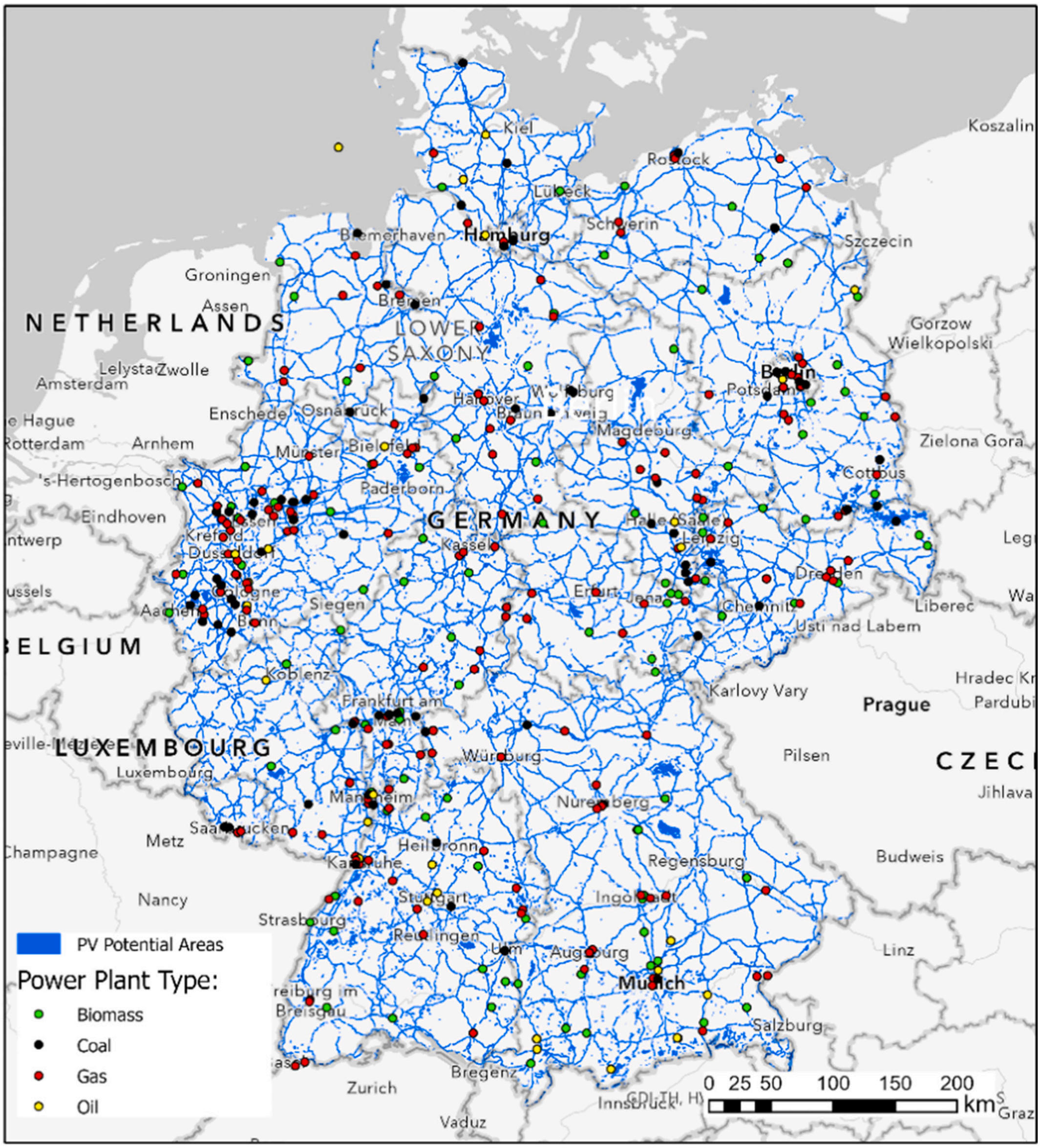

Fig. 6. Potential PV areas alongside roads (marked blue) and conventional power plants that could be transformed to TSPP, as mentioned before. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

area of approximately 15,236 km^2 for PV installation throughout Germany of which only 1575 km^2 would be required for TSPP.

2.5. Biomass Atlas for TSPP in Germany

In the analysis at hand, not only the PV potential areas shall be considered. In actual applications, identifying the biomass potential resources and biomass transportation solutions is also essential when transforming conventional power plants to TSPP. In this section, the method of finding potential biomass resources will be introduced.

Since the main goal of using TSPP is to utilize carbon-neutral resources wherever possible, as well as not taking up wood reserves other than for energy purposes, only residual biomass will be considered as potential bioenergy source, and others, such as energy crops are not considered as an alternative option in this paper. The following residual biomass resources are considered as feasible:

- Grain straw
- Spare forest wood
- Biowaste from city

Grain straw is waste from agricultural lands. According to the research report from DBFZ [20], the grain straw potential is distributed over different municipalities. The necessary geoinformation has been uploaded to the geographic information system, and then overlapped with the agricultural area in this region obtained from global land cover database (marked as pink in Fig. 7) [15]:

$$Grain\ Straw = \frac{Total\ grain\ straw\ potential\ in\ the\ municipality}{Total\ agricultural\ area\ in\ the\ municipality}\ \left[\mathrm{MWh_{th}}/\mathrm{km}^2\right] \quad (1)$$

Fig. 7 shows the energy density of grain straw in different municipalities. As seen in this figure, the potential of grain straw is highest in northern Germany, especially in the region of Mecklenburg-Vorpommern.

Wood resources are Germany's strong point. According to the third Federal Forest Inventory, about 32 % of the total land area in Germany is forest area, which is about 114,400 km^2 [22]. In addition, the forest area is evenly distributed over the country, which is convenient for future biomass supply to TSPP. Potential data for each municipality was calculated by dividing the total wood potential in Germany by the total forest area. This number is then multiplied with the forest area of each municipality, which has been obtained from global land cover database (marked as green). This method allows for the estimation of potential wood resources in each municipality for the transformation of conventional power plants into TSPP. Fig. 8 shows the resulting total sustainable forest wood potential in Germany per municipality.

$$\text{Wood potential per municipality} = \frac{\textit{Total wood potential in Germany}}{\textit{Total forest area in Germany}} * \textit{Forest area per municipality} [\mathrm{MWh_{th}}/\mathrm{Municipality}] \quad (2)$$

The utilization of bio-waste from urban areas is another viable source of energy for TSPP. It encompasses kitchen waste generated by citizens, leaves and branches from parks, and bio-waste from lawn mowing activities. While the bio-waste stream is considered small compared to the total bioenergy potential in Germany, it remains a contributor to the overall biomass potential. The potential data is also available per municipality, which is obtained from global land cover database (marked as red) (Fig. 9).

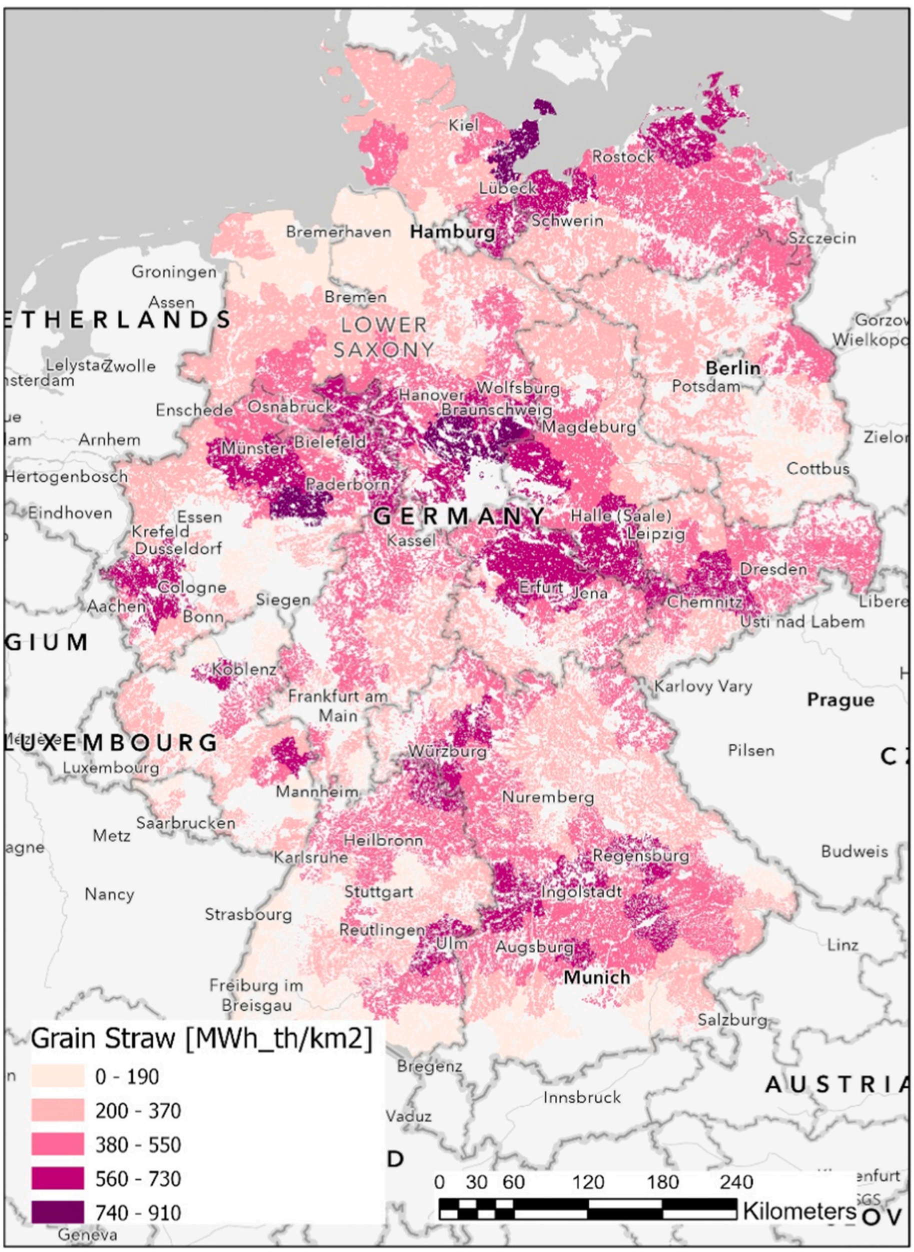

Fig. 7. Grain straw potential in Germany [21].

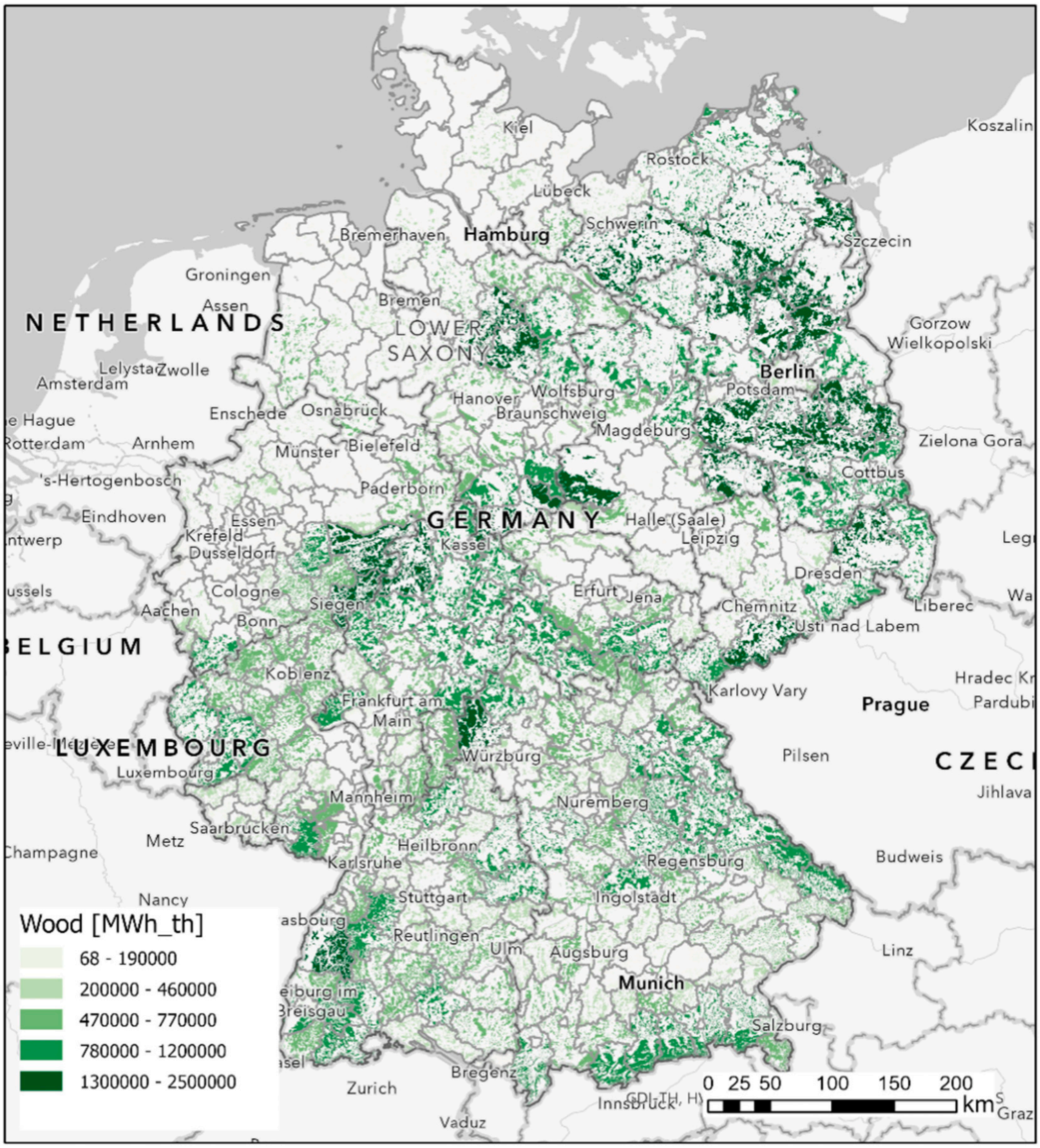

Fig. 8. Wood potential in Germany per municipality [21].

These three forms of biomass constitute the sum of potential residual bioenergy in our scenario.

2.6. Method of finding the suitable PV/biomass areas for TSPP considering power plant ranking

The method of finding the suitable areas is based on the "concentric circle method" from [9]. The method employed in the analysis uses the power plant as the center of the circle and iteratively expands the concentric circles to determine whether the surrounding area meets the requirements of the power plant transformation. As shown in Fig. 10, the circle around each potential TSPP is continuously expanded and overlapped with the potential PV and biomass areas (marked yellow). The common region of the overlapping areas is then calculated and considered as a potential resource development area for this specific plant (marked green).

For PV areas, this calculated area will be transformed into PV capacity. If this PV capacity is larger than the one required by the power plant, then sufficient PV installation area has been found to meet the energy demand. For biomass areas, the cut area will be translated into related biomass thermal energy. The thermal energy that can be obtained from grain straw, wood and urban waste is calculated separately and finally added to obtain a total. If this total thermal energy is larger than the energy demand of the power plant, then there is enough potential biomass area to meet the energy demand of the TSPP.

If the value is smaller than the requirement, the radius will be extended by 100 m to check whether this time the area is large enough or not. If the circle exceeds the country border, but the overlapping area still cannot fulfill the demand of the power plant, for PV analysis we consider this power plant as not suitable to be transformed into a storage plant, and it is set to a lower priority on the ranking list. For biomass simulation, if the analysis did find some area for this TSPP, however not enough for the requirement, the deficit will be filled up theoretically by bioenergy imports from neighboring countries, and this power plant is still considered as available for transformation. If all the biomass potential is used up by power plants with higher priority in the ranking list, and the latter power plant requires 100 % bioenergy imports, then this power plant will not be considered as available for transformation, just like all other plants following with lower priority.

Fig. 11 shows the flow chart of the whole analysis for Germany. The act of finding the necessary PV and biomass area is performed simultaneously. Only when both the required PV area and sufficient biomass

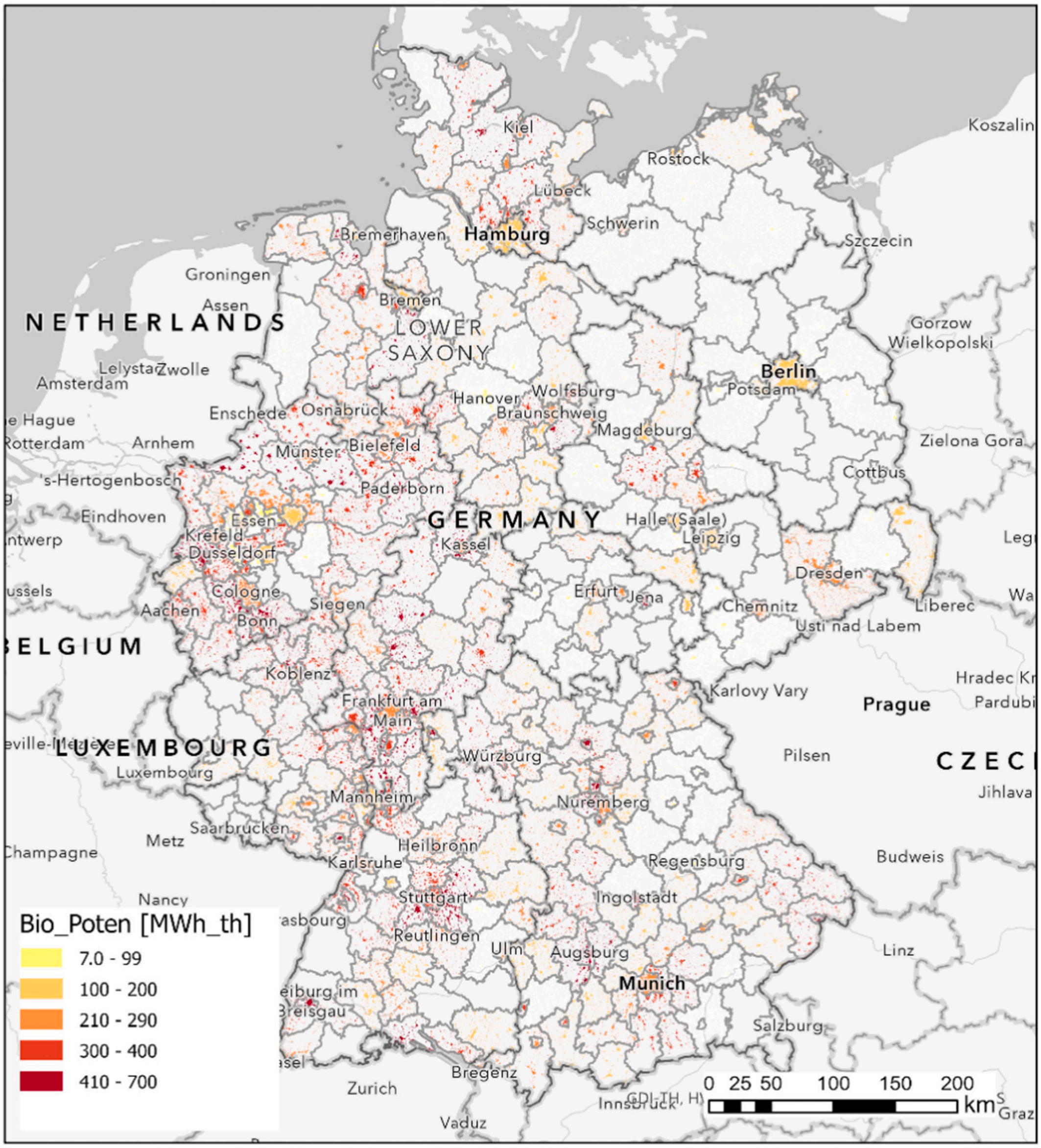

Fig. 9. City bio waste in Germany. These values will be assigned to urban areas from global land cover database per City. (Marked as red) [21]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

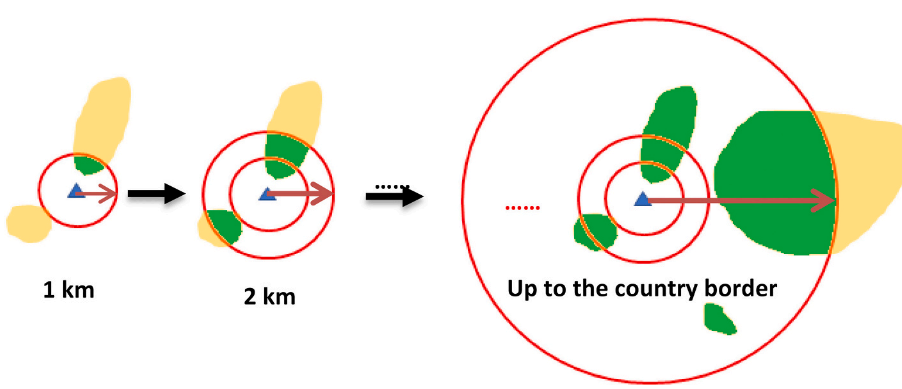

Fig. 10. Algorithm of finding suitable PV/Biomass areas for a power plant unit.

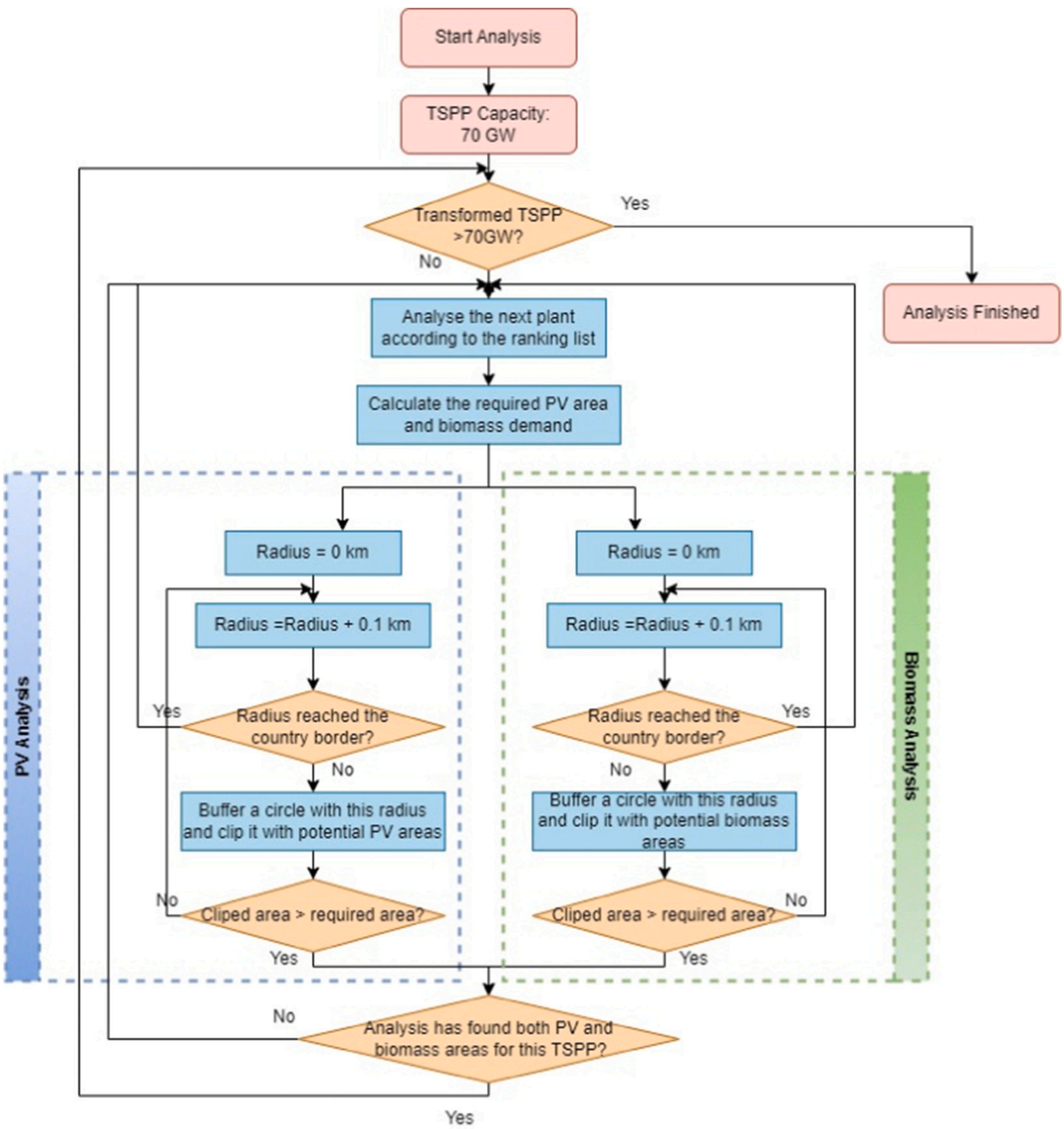

Fig. 11. Flowchart of finding suitable PV/Biomass areas for a power plant unit.

Table 5
List of parameters.

P_{TSPP}	TSPP Capacity (MW)
$P_{Original}$	Capacity of the original fossil power plant (MW)
P_{GT}	Capacity of the newly installed gas turbine in TSPP (MW)
P_{ST}	Capacity of the newly installed steam turbine in TSPP (MW)
$E_{Biomass}$	Biomass demand for a specific TSPP (MWh_{th})
$E_{Natural\ gas}$	Natural gas demand for a specific TSPP (MWh_{th})
$E_{annual\ generation}$	Annual power generation for a specific TSPP (GWh_{el}/a)
$m_{CO2,TSPP}$	Specific CO2 emission per GWh of electricity of TSPP (t_{CO2}/GWh_{el})
$m_{CO2,Original\ oil\ PP}$	Specific CO2 emission per GWh of electricity of oil power plant (t_{CO2}/GWh_{el})

area are found, they will be reserved for this certain power plant. Otherwise, these areas will be released, and the search for suitable areas for the next power plant in the priority ranking begins.

3. Data and assumptions

In this section, the sources, as well as the values of the parameters mentioned above will be explained. Table 5 shows the parameters used in this paper.

Table 6
Capacity changes of different types of conventional power plants after transformation to TSPP.

Original power plant capacity $P_{original}$	TSPP capacity P_{TSPP}	
Steam turbine power plant ≤ 25 MW	$P_{TSPP} = P_{original} + P_{GT} = P_{original} + 2.5 * P_{original}$	Eq.3
Steam turbine power plant >25 MW	$P_{TSPP} = P_{original} = P_{original}/(1 + 2.5) + P_{original}/(1 + 2.5) *2.5$	Eq.4
Gas turbine power plant	$P_{TSPP} = P_{original} + P_{ST} = P_{original} + P_{original} / 2.5$	Eq.5
Combined cycle power plant	$P_{TSPP} = P_{original}$	Eq.6

3.1. Parameters for TSPP capacity

When transforming conventional power plants (steam cycles, gas turbines or combined cycles) to TSPP, because a new additional turbine (gas turbine or steam turbine) will be installed during the plant transformation, the total capacity will be increased compared to the original plant, except for combined cycles, where gas turbine and steam turbine will be used just as already available.

According to the analysis from [1,8], the ratio of the steam turbine to the gas turbine in a certain TSPP is approximately 1:2.5. For gas turbine power plants, the capacity of the steam turbine that has to be added is about 40 % of the original gas turbine capacity. When it comes to combined cycle power plants, because the existing equipment already consists of a steam turbine and a gas turbine, there is no need to change their capacity.

For steam turbine power plants with small capacities ($\leq$ 25 MW), an additional gas turbine with a capacity of 2.5 times bigger than the original power plant will be installed. For very large steam turbine power plants, it is unrealistic to install an even 2.5 times bigger gas turbine. Thus, the original capacity of it will be kept unchanged. However, the old steam turbine will be removed, and a new steam turbine and a new gas turbine will be installed with a ratio of 1:2.5. In other words, the original capacity will be divided into 3.5 portions, with the steam turbine of the transformed TSPP accounting for one portion, and the gas turbine accounting for 2.5 portions. Table 6 shows how TSPP capacity after transformation is calculated from the original power plant capacity:

3.2. Parameters for the PV Atlas

Usually, the capacity of PV for TSPP is determined by many different factors, such as the steam turbine capacity, the location of the power plant, the solar radiation, the geographic situation of the TSPP, etc. According to [1], a factor named Solar Plant Power Ratio (SPR) is defined to determine the capacity of the PV as function of the capacity of the TSPP's steam turbine. In the case of Germany, the SPR for every installed TSPP is assumed to be 5, which means that for the scenario of installing 70 GW TSPP in 2040 in Germany, including 21 GW steam turbine, about 105 GW PV should be newly constructed for TSPP. Assuming that 1 MW PV takes an installation area of about 0.015km^2, the total land area demand for PV installation is about 1575 km^2 [9,23].

3.3. Parameters for the Biomass Atlas

According to [24], the grain straw biomass potential in Germany is about 16 million tons (dry mass) in total per year. With the heat value of grain straw of 4.86 MWh/t [25], the total grain straw potential in Germany amounts to about 78 TWh$_{th}$/a. The biowaste potential from urban areas is about 6 TWh$_{th}$/a [24].

As shown in Fig. 12, the wood potential in Germany is about 204 TWh$_{th}$/a [22]. This value refers to the quantity of wood that naturally grows each year, excluding the amount that needs to be preserved due to relevant policies and ecological (environmental) requirements. It is worth mentioning that this portion of wood cannot be entirely utilized for power generation as there are also other purposes, such as industrial use, etc. However, determining the proportion for the different specific usage is challenging. In this paper, we temporarily consider the entire quantity of wood as the potential resource, and after the transformation analysis, we assess the actual usage of wood to determine if this result aligns with real-world conditions.

While calculating the total potential of these biomass resources, greenhouse gas emissions due to various reasons, such as transportation, processing, etc., should also be taken into account. Therefore, greenhouse gas savings are not 100 % when substituting fossil fuels by bioenergy. Fig. 13 introduces the greenhouse gas savings from typical types of biomasses in comparison to fossil fuel in EU. The detailed method of this calculation is explained in [26,27].

Table 7 shows typical greenhouse gas emissions from different types of solid biomass. It is noticeable that using different process fuel on the same raw biomass resources will cause a significant difference on greenhouse gas emissions.

According to [8], in 2040 TSPP will generate about 213 TWh/a of electricity in order to cover the residual load in Germany. Power from TSPP consists of basically 3 parts: PV provides directly 45 TWh electricity to the grid; steam turbines will generate about 103 TWh/a coming from co-firing, the heat recovery steam generator (HRSG) and the thermal energy storage; the gas turbine contributes about 65 TWh electricity and consumes 176 TWh$_{th}$/a of natural gas. The energy flow of the TSPP components is shown in Fig. 14. The efficiencies of different components are assumed from [13], Table 2.

In order to reduce the consumption of fossil fuels as much as possible, TSPP use about 141 TWh$_{th}$/a of bio-coal, wood or straw pellets as backup fuel. The TSPP's gas turbines still use natural gas, that in the future could be subsequently replaced by biomethane [28].

4. Results

4.1. Downscaling of power plant capacity and fuel consumption

According to Table 1 and Fig. 14, about 70 GW TSPP will be newly constructed or transformed in 2040, and this consists of 21 GW steam turbines and 49 GW gas turbines. The steam turbines will consume a total of 141 TWh$_{th}$/a of biomass, and the gas turbines will consume a total of 176 TWh$_{th}$/a of natural gas.

In order to calculate the specifications and fuel consumption of a specific power plant after its transformation to TSPP, it is necessary to downscale the overall capacities of the scenario to that single plant. The required amount of bioenergy can be calculated based on the capacity of the steam turbine of the TSPP:

$$E_{Biomass} = \frac{P_{ST}}{P_{ST,Total}} \bullet E_{Biomass,total} \tag{7}$$

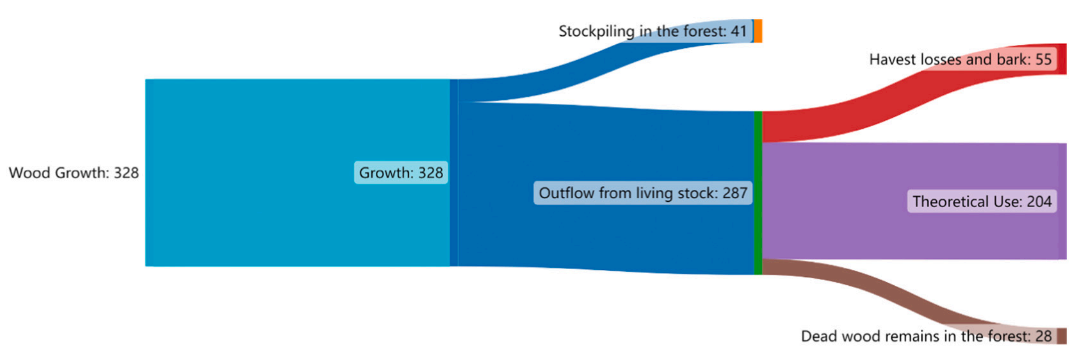

Fig. 12. Sankey-Diagram of wood energy flow in Germany. Values represent the lower heating value in TWh$_{th}$ [22].

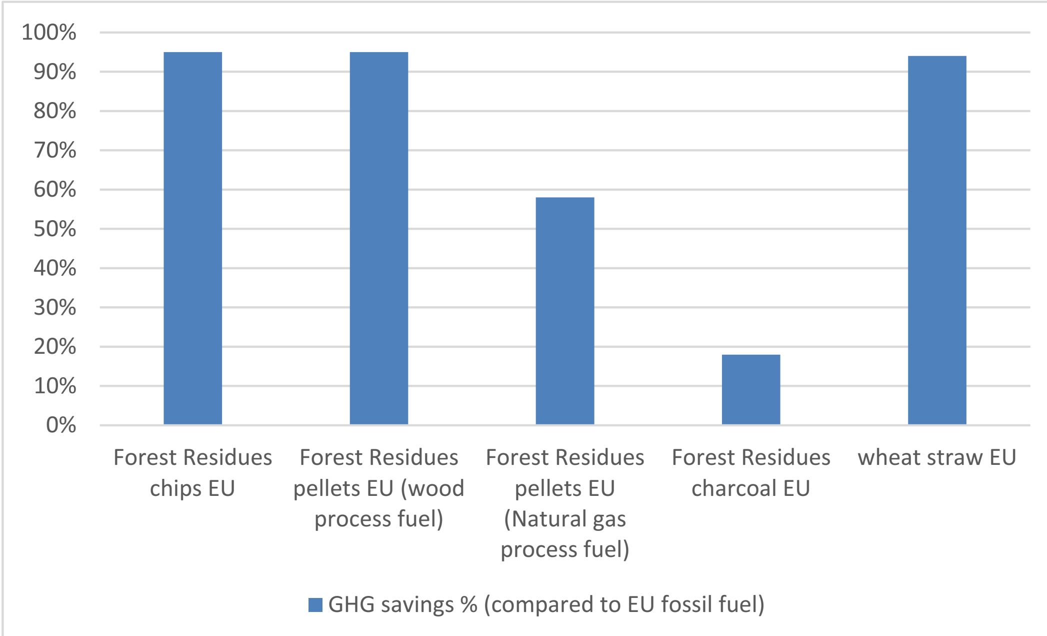

Fig. 13. Typical greenhouse gas mitigation performance of solid biomass [26,27].

Table 7
Default greenhouse gas emissions for solid and gaseous biomass [26,27]. The indicated GHG are related to contemporary handling and transformation processes of biofuels that still rely partially on fossil fuels. In the long-term future, it can be expected that fossil fuels are generally replaced by renewable primary energies in all industrial sectors, also avoiding those emissions.

Primary solid biomass pathways	Default greenhouse gas emissions [gCO_2eq/MJ]
Wood chips from forest residues (European temperate continental forest)	1
Wood briquettes or pellets from forest residues (European temperate continental forest) – using wood as process fuel	2
Wood briquettes or pellets from forest residues (European temperate continental forest) – using natural gas as process fuel	35
Charcoal from forest residues (European temperate continental forest)	41
Wheat straw	2

It is worth mentioning that the biomass demand per TSPP capacity for a combined cycle power plant is different from other types of TSPP (Table 8). As mentioned earlier, for typical original steam turbine and gas turbine power plants, the capacity ratio of them after the transformation is 1:2.5. However, in the case of a combined cycle power plant converted to a TSPP, the ratio of steam turbine to gas turbine capacity remains at 1:2 in order to save the capital costs, resulting in different outcomes between these two types of power plants:

$$E_{Biomass,combined\ cycle} = \frac{\frac{1}{3}P_{TSPP}}{21\ GW} \bullet 141 TWh_{th}/a \approx 2239[MWh_{th}/MW] \bullet P_{TSPP} \tag{8}$$

$$E_{Biomass,others} = \frac{\frac{1}{3.5}P_{TSPP}}{21\ GW} \bullet 141\ TWh_{th}/a \approx 1920[MWh_{th}/MW] \bullet P_{TSPP} \tag{9}$$

In addition, it is also necessary to calculate the natural gas demand for the TSPP gas turbines. However, this demand cannot be simply calculated by scaling it proportionally, as is done with the biomass demand, because the ratio of transformed gas turbine to steam turbine differs between CC and typical TSPP. Instead, this ratio has also been scaled to calculate the natural gas demand:

$$E_{Natural\ Gas} = \frac{P_{GT}}{P_{GT,Total}} \bullet \left(\frac{P_{GT}}{P_{ST}} \bullet \frac{P_{ST,Total}}{P_{GT,Total}}\right) \bullet E_{Natural\ Gas,total} \tag{10}$$

$$E_{Natural\ Gas,Combined\ cycle} = \frac{\frac{2}{3}P_{TSPP}}{49\ GW} \bullet \left(\frac{2}{1} \bullet \frac{21\ GW}{49\ GW}\right) \bullet 176\ TWh_{th}/a \approx 2058[MWh_{th}/MW] \bullet P_{TSPP} \tag{11}$$

$$E_{Natural\ Gas,others} = \frac{\frac{2.5}{3.5}P_{TSPP}}{49\ GW} \bullet \left(\frac{2.5}{1} \bullet \frac{21\ GW}{49\ GW}\right) \bullet 176\ TWh_{th}/a \approx 2757[MWh_{th}/MW] \bullet P_{TSPP} \tag{12}$$

Table 8 summarizes the specific bioenergy demand and natural gas demand per installed TSPP MW of power capacity of different types of conventional power plants after transforming them to TSPP, following the scenario presented before.

In this paper, a specific power plant with low ranking for transformation to TSPP has been randomly selected from our database in order to demonstrate the downscaling procedure (Table 9).

As a first step, the capacity of the complementing gas turbine after transformation to TSPP of 47.5 MW is calculated according to Table 6 for the existing steam turbine of 19 MW, leading to a TSPP with a total capacity of 66.5 MW.

In the case of the example power plant, the total power generation per year is about:

$$E_{annual\ generation} = P_{TSPP} \bullet \frac{E_{Total,TSPP}}{P_{Total,TSPP}} = 66.5\ MW \bullet \frac{213 TWh/a}{70\ GW} \approx 202\ GWh_{el}/a \tag{13}$$

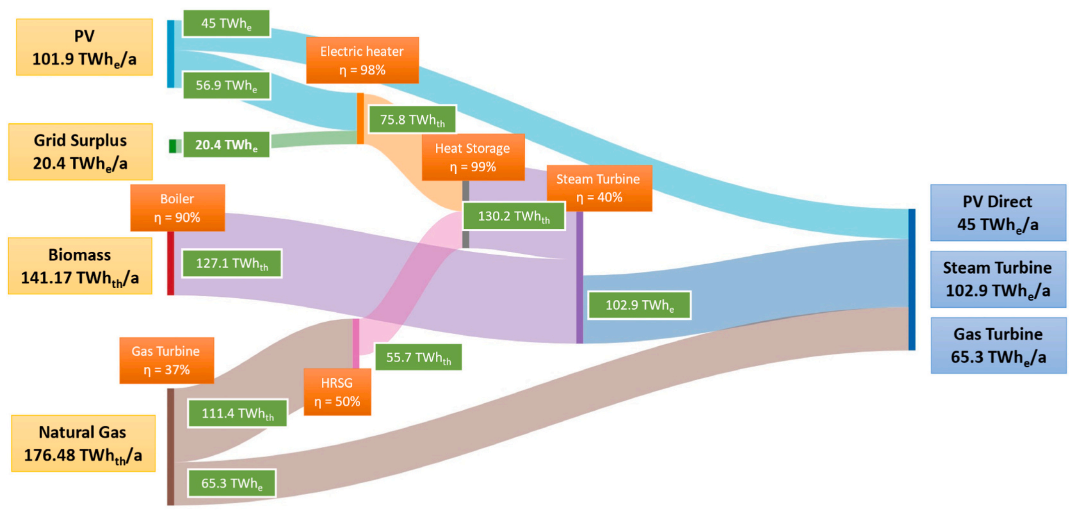

Fig. 14. Energy flow of TSPP power generation in Germany (Loss flows are not displayed).

Table 8
Biomass and natural gas demand from different types of conventional power plants after transformation to TSPP. Numbers indicate the lower heating value of solid biomass per MW of total installed power capacity of the TSPP (including steam turbine and gas turbine) required for backup firing for steam generation. This information is used by the geographic information system for the search of the necessary biomass potentials around each power plant.

Original Power plant type	Biomass demand after transformation to TSPP [MWh_{th}/MW_{TSPP}]	Natural gas demand after transformation to TSPP [MWh_{th}/MW_{TSPP}]
Coal/Oil/Gas-fired steam power plant	1920	2757
Biomass steam power plant	1920	2757
Gas turbine power plant	1920	2757
Combined cycle power plant	2239	2058

Table 9
Data sheet of the power plant with low-ranking priority selected randomly as example.

Power plant unit	RHEINLAND RAFFINERIE 2
Plant	RHEINLAND RAFFINERIE Energy and Chemicals Park Rheinland
Geographic location	(50.855, 6.980)
City	Cologne, Germany
Company	Shell Deutschland Oil GmbH
Capacity	19 MW
Operating status	Operating
Operation year	1966
Turbine Type	Steam turbine
Fuel	Oil
Ranking	No. 412

Table 10
Summery of electricity yield and fuel consumption of the example power plant, calculated by downscaling the parameters of the reference scenario.

	Reference Scenario			Example Plant No. 412		
Component	Power	Yield	Fuel	Power	Yield	Fuel
	GW	TWh/a	TWh_{th}/a	MW	GWh/a	GWh_{th}/a
Steam Turbine	21	103	141	19	93	128
PV stored	–	22	–	–	20	–
HRSG	–	30	–	–	27	–
Bio-Backup	–	51	141	–	46	128
Gas Turbine	49	65	176	47.5	68	183
PV total	105	105	–	95	95	–
PV direct	–	45	–	–	41	–
Total TSPP	70	213	318	66.5	202	311

In this equation, according to Table 8, the demand for biomass for the steam turbine is about:

$$E_{Biomass} = P_{TSPP} \bullet 1920 MWh_{th}/MW = 66.5\ MW \bullet 1920\ MWh_{th}/MW \approx 128\ GWh_{th}/a \tag{14}$$

The natural gas consumption of the single TSPP in our example is then:

$$E_{Natural\ Gas} = P_{TSPP} \bullet 2757 MWh_{th}/MW = 66.5\ MW \bullet 2757 MWh_{th}/MW \approx 183\ GWh_{th}/a \tag{15}$$

Table 10 summarizes the contributions to power generation of the different TSPP components and their fuel consumption, calculated by downscaling the energy scenario to the single plant capacities. The total fuel consumption of the example power plant is about 311 GWh_{th}/a.

A central point of interest is to calculate the greenhouse gas emissions generated by the TSPP after its transformation. According to the report from UBA [28,29], the greenhouse gas factor of natural gas is about $n_{CO2,Natural\ Gas} = 242$ t/GWh_{th}. Therefore, the greenhouse gas emissions from the example power plant after transformation to TSPP are approximately:

$$\mathrm{m}_{CO2,TSPP} = \mathrm{E}_{Natural\ Gas} \times \mathrm{n}_{CO2,Natural\ Gas} = 183 GWh_{th}/a \bullet 242 t_{CO2}/GWh_{th} \div 202\ GWh_{el}/a \approx 219\ t_{CO2}/GWh_{el} \tag{16}$$

For comparison, assuming a typical efficiency of the oil-fired steam cycle of $\eta_{Oil} = 37.5$ % and a specific carbon footprint of $n_{CO2,Oil} = 315$ t/GWh_{th} for fuel oil, the specific carbon emission per GWh of electricity of the original plant before its transformation to TSPP was approximately around:

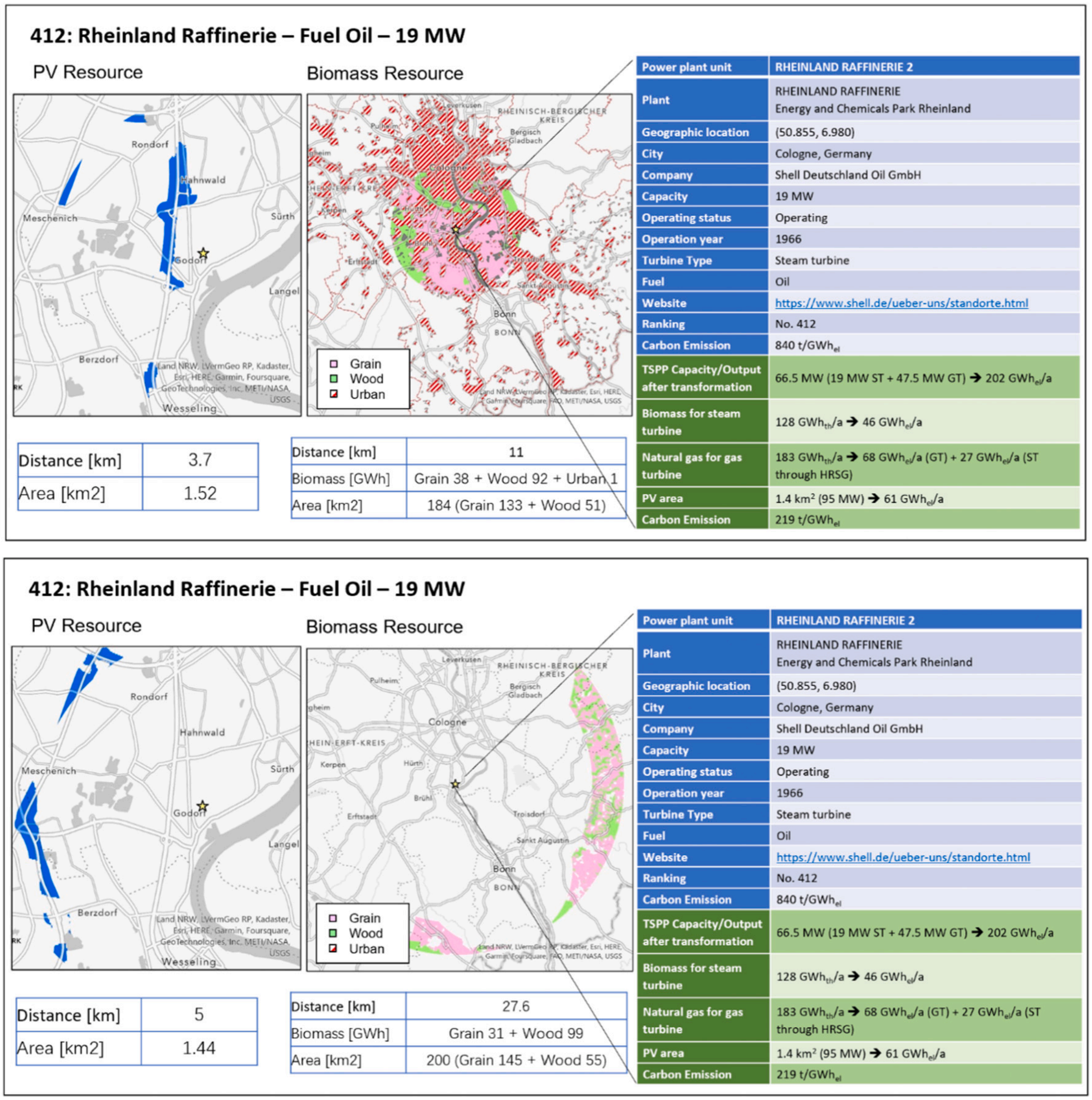

Fig. 15. The complete analysis results of the transformation of power plant Rheinland Raffinerie 2 to TSPP. Top: Analysis without considering the power plant ranking Bottom: Analysis considering the power plant ranking. The specific power plant was randomly selected as example page of the German TSPP Atlas.

Table 11
Summery of conventional power plant capacity selected for potential transformation to TSPP.

Power plant type by fuel	Capacity before transformation [MW]
Biomass	1450
Coal	37,282
Gas	19,400
Oil	2331

$$m_{CO2,Original\ Oil\ PP} = n_{CO2,Oil} \div \eta_{Oil} = 315 t_{CO2}/GWh_{th} \div 37.5\% \approx 840\ t_{CO2}/GWh_{el} \tag{17}$$

The carbon emissions from biomass in TSPP are excluded in the calculation. As mentioned earlier in the paper, TSPP primarily utilizes straw and wood as the main sources of biomass. We put Fig. 13 and Table 7 in the previous section precisely to demonstrate that straw and wood result in a reduction of over 95 % in carbon emissions compared to fossil fuels, making them negligible in the calculations. Furthermore, from a policy perspective, biomass is considered a zero-carbon fuel under current EU policies [30]. Hence, we omitted it from the calculations.

4.2. Result without power plant ranking

The initial analysis does not look at the macro level of the country, but at the micro level. Unlike the German energy scenario, which focused on demonstrating the feasibility of the plant transformation solution at the national level, the first analysis focuses more on the optimal solution that a particular power plant can find in terms of PV installation area and biomass source when facing transformation.

This analysis is more in line with the analysis of specific projects. When analyzing a specific power plant, the first-come, first-served principle is followed, and the ranking list will no longer apply for all power plants in a certain country.

Fig. 15 shows the two different results regarding suitable PV areas. As shown in this figure, the resulting average distance between the PV and power plant not applying a ranking is smaller than that obtained from the analysis with ranking. According to the result, the distance without the ranking is about 3.7 km, while the distance with the ranking is 5 km, because according to the first analysis, other plants would have higher priority to be transformed to TSPP.

As to biomass areas, there is a significant difference in the analysis of biomass areas between the two approaches. Without the ranking, the biomass resources are just in the near vicinity of the power plant, within an average radius of approximately 10.7 km.

The results of the above analysis of the plant Rheinland Raffinerie 2 and the calculation of CO_2 emissions for the TSPP allowed us to come up with a complete transformation solution for this particular plant. The results including maps and datasheet for each plant are compiled in one page of the German TSPP atlas as shown in Fig. 15, top.

4.3. Results with power plant ranking

The second analysis entails a national-level assessment aimed at installing or transforming 70 GW of TSPP in Germany by 2040. The key objective of this analysis is to prioritize the allocation of potential land areas to achieve this goal. To this end, a comprehensive ranking of the existing power plants is necessary.

With this purpose, a thorough examination of 645 conventional power plants with an original capacity of 60.4 GW in Germany was conducted, leading to the following results. Table 11 shows the statistics of the analyzing result regarding the capacities of 4 types of conventional power plants before the transformation. At a macro level, the hypothetical transformation of those conventional power plants to 70 GW TSPP has been achieved successfully. The capacity of existing power plants has been expanded according to Table 6.

As per the analysis results, the installation of 70 GW of TSPP would require an area of 1547 km^2 dedicated to PV installation alongside highways, amounting to approximately 0.4 % of German total land area, considering the power plant ranking. This result is slightly lower than that of the reference scenario. The transformation process would require the use of 44.7 TWh_{th} of grain straw, which constitutes roughly 50 % of the national total grain straw reserve. At the same time, 93.8 TWh_{th} of wood would be reserved for TSPP, which is equivalent to about 46 % of the identified wood potential in Germany.

Fig. 15, bottom shows the results of the example power plant regarding the required PV and biomass areas. As the ranking of the example plant is rather low (No.412), when considering other higher-ranking power plants, the nearest biomass areas are already reserved by them, forcing the example plant to look for PV and biomass resources further away, resulting in a distance of around 27.6 km for biomass outside the range of the city areas.

An additional point worth noting is that as shown in Fig. 15, the PV areas and the biomass areas from the analyzing results, are slightly larger than the calculated TSPP demand in the table on the right side (top: 131 GWh_{th} biomass found, 128 GWh_{th} required, and bottom: 130 GWh_{th} biomass found, 128 GWh_{th} required). The reason is that the radius accuracy of the analysis is 100 m. When the area does not meet the requirements, the radius is expanded by 100 m and reanalyzed. As a result, the delineated area is sometimes significantly enlarged and exceeds the required size. This difference can be reduced by decreasing the radius accuracy, for example, 10 m, but the analysis time will be significantly increased.

5. Discussion, conclusion and outlook

The main objective of this article is to analyze the potential of PV and residual biomass energy in Germany and utilize GIS software as a tool to analyze whether TSPP can be allocated near sufficient PV and biomass resources within a reasonable range from a geographical perspective. The final goal is to find out the feasibility of the basic TSPP scenario for the year 2040 published before [8].

Briefly, the process of establishing a TSPP atlas consists of several parts. The first step is the development of a scenario through the ELCALC tool based on the country's specific situation and energy policy, which is described in [8], such as the load pattern of different types of power plants and the supply patterns of various renewable power plants. At the same time, for the TSPP itself, it is necessary to determine its layout and the size of each component to ensure that it can supply the residual load in an optimal way. [10,13] have elaborated on the layout of TSPP, the efficiency of each component, etc. In addition, the expected cost reduction with this specification of TSPP is also calculated in detail in these two papers.

With this information as basis, the final step is to build the TSPP atlas, which is built through a series of algorithms based on the existing database of thermal power plants (containing basic information about the plants and their geographical locations), combined with information about the country's photovoltaic and bioenergy resources. From this, at the macro level a ranking list for the plant transformation can be achieved; and at the micro level the potential PV area and bioenergy locations after the transformation of each TSPP itself can be derived. The above results together provide a reliable and feasible solution for the national energy transition towards 100 % renewable electricity supply.

The final outcome is an atlas compilation for the potential transformation of conventional power plants to TSPP in Germany. It includes the locations and relevant physical characteristics of each TSPP, aiming to meet the basic energy scenario for 2040. Additionally, it incorporates the corresponding areas for photovoltaic installations and the sources of biomass energy. From a macro perspective, this atlas provides decision-makers with a solution for the energy transformation with TSPP. It demonstrates the feasibility of transforming traditional thermal power plants into TSPPs from a national perspective, aligning with the energy scenario. From a micro perspective, this atlas also serves as a reference for each potentially transformed power plant. Future transformation projects for specific power plants can consult this atlas in order to quickly access relevant geographical information and the nearby resources.

In the future, the following points will be considered as further research directions for other countries: The first direction is to try to completely avoid using fossil power plants. In this paper, TSPP still uses natural gas as fuel for the gas turbines. However, in the future, biomethane would be a viable option to replace natural gas to avoid carbon emissions, high fuel cost as well as high CO_2 cost [31].

For some countries, if the residual biomass is not sufficient for TSPP transformation, importing biomethane or bio-coal from residual biomass from neighbor countries may be an acceptable solution. In addition, for some countries with lower biomass resources, optimizing the TSPP model is also a good way to reduce the usage of biomass. Expanding the PV usage can significantly reduce the biomass/backup heat demand, if better solar energy resources are available like e.g., in Chile [32].

CRediT authorship contribution statement

Pai Liu: Methodology, Software, Formal analysis, Writing – original draft, Funding acquisition. **Franz Trieb:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled.

Data availability

Data will be made available on request.

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4. Summary and discussion

The above three papers based on this dissertation have investigated solutions for the transformation of conventional power plants to TSPP from three perspectives. The first publication has answered three questions: which conventional thermal power plants can be potential candidates for transformation into TSPPs, how to rank these thermal power plants, and what is the PV potential areas in Germany. After analysis, a first approach of a TSPP-related PV-Atlas in Germany is determined. The second publication focuses on the cost comparison of conventional power plants and the TSPP after transformation through calculating their levelized cost of electricity (LCOE) in order to prove that TSPP can reduce the carbon emissions, and at the same time, reduce the power generation costs. The third publication has on one hand established a TSPP-related Biomass-Atlas in Germany, and on the other hand an improved the PV-Atlas from the first paper. Finally, a combined TSPP-Atlas in Germany is established. In this section, an overall result of the dissertation and the discussion of this result is provided.

4.1 Ranking potential conventional power plants to be transformed to TSPP

With the selection of power plants according to the first paper, the following three types of power plants were selected as potential candidates for transformation:

- Steam turbine power plants;
- Gas turbine power plants (Single cycle);
- Combined cycle power plants

In terms of fuel, the following types of power plants were taken into consideration:

- Coal/ Lignite fired power plants;
- Oil fired power plants;
- Gas fired power plants;
- Biomass fired power plants

This approach allows us to leverage the existing equipment during the transformation process, leading to capital cost savings. Moreover, it relatively provides convenience in terms of accessing biomass and natural gas resources. Only power plants that meet four selection criteria will be considered. After the selection process, approximately 645 thermal power plant units in Germany were identified as potential candidates for transformation [21][22].

Once the list of potential power plants was established, it was possible to achieve the 70 GW transformation target by selecting only a portion of the listed power plants. The next step was to identify the most suitable power plants for TSPP transformation, prioritizing them to receive PV installation areas and biomass resources. Table 3 has provided the ranking criteria for these conventional power plants. The evaluation was conducted based on four aspects, with scores ranging from 1 to 4.

Table 3: Ranking criteria of power plants for transformation to TSPP

Power Plant Properties	Score			
	1,0	*2,0*	*3,0*	*4,0*
Age	<20 y	20-40 y	>40 y	-
Power Plant Capacity	<100 MW	100-250 MW	250-500 MW	>500 MW
Steam Temperature	<=565 °C	>565 °C	-	-
Fuel	Biomass	Fossil fuels	-	

Table 4: Ranking levels of the power plants

Scores				Ranking Levels
1,0	*2,0*	*3,0+*	Total	
4	-	-	4	A
3	1	-	5	B
3	-	1	6	C
2	2	-	6	C
2	1	1	7	D
1	3	-	7	D
2	-	2	8	E
1	2	1	8	E
-	4	-	8	E
1	1	2	9	F
-	3	1	9	F
1	-	3	10	G
-	2	2	10	G
-	1	3	11	H

After scoring, each power plant is assigned a score based on its physical characteristics. These individual scores are then summed up to obtain a total score, which is used to determine the final ranking level for each power plant. Power plants that are rated as Class A will be given priority in selecting PV installation areas, and so on in descending order. Table 4 shows the final ranking levels of the thermal power plants.

4.2 Assessment of potential PV areas

The next step is to determine Germany's photovoltaic potential and the corresponding installation areas. According to the paper I and paper III, based on the TSPP model, the total capacity of photovoltaics within the TSPP is approximately 5 times the total capacity of the steam turbines in TSPP, which amounts to a total of 105 GW [20]. Considering Germany's solar radiation conditions, this roughly refers to an installation area of 1575 km^2 for photovoltaics.

To determine where the photovoltaics can be installed, GIS software is once again used [23]. Firstly, it is necessary to incorporate a database of global landcover in Germany, from which the following four kinds of land are considered suitable for photovoltaic installation [24]:

- Cultivated land [25];
- Grass land;
- Bare land
- Shrub land.

Next, protected areas need to be excluded from these land attributes. Additionally, regarding cultivated lands, not all areas of it can be used for PV installation [27][28][29][30][31]. In this case, only the cultivated land within a distance of 200 meters on both sides of highways is considered as potential PV installation areas. The total area of these potential PV installation is about 15,000 km^2.

4.3 Cost comparison of TSPP and conventional power plants

The second aspect worth researching in terms of TSPP transformation is the economic analysis. In paper II, some representative conventional power plants will be selected and transformed into TSPPs. During this process, the levelized cost of electricity (LCOE) will be calculated before and after the transformation to assess the difference in power generation costs. LCOE of both power plants consists of the following parts: Capital costs, operation costs, fuel costs and carbon dioxide costs.

To minimize the TSPP costs, the transformation process aims to retain the existing components of the initial power plants as much as possible. The main source of change in LCOE before and after the transformation lies in the usage of fuel. With TSPP primarily relying on solar energy, the dependence on fuel, especially fossil fuels, is significantly reduced. The final crucial point to consider is the price of carbon dioxide (CO_2). In this paper, the CO_2 price is set at 55 Euro/t, and biomass is assumed to be a carbon-neutral fuel [32]. This significantly reduces the expenditure of TSPPs on CO_2 emissions.

After obtaining the information mentioned above, the LCOE can be calculated for each type of thermal power plant before and after the transformation [33]. From the result shown in Table 5, it is observed that the LCOE of the TSPPs has significantly decreased compared to the original power plants, though causing more capital costs. This reduction is attributed to the decreased reliance on fossil fuel and the increased utilization of bioenergy as backup energy source. This characteristic implies that TSPPs are less affected by energy price fluctuations, which can be more and more important as the energy prices continue to rise and experience volatile fluctuations.

Table 5: Levelized cost of energy of conventional power plants and their transformed TSPP [33]

LCOE [Euro/MWh]	*Original power plant*	*TSPP*
Combined Cycle natural gas	241	135
Gas turbine natural gas	343	144
Coal steam cycle	201	152
Biomass steam cycle	234	149

4.4 Assessment of potential biomass areas

The analysis of Germany's biomass potential follows a similar approach to PV potential, researching both the demand and supply aspects. From the demand perspective, the biomass requirement for the 70 GW TSPPs after transformation can be calculated based on the TSPP-MOD configuration. From the calculations in paper III, it can be concluded that the TSPPs will require approximately 141 TWh of thermal energy after transformation.

From the supply side, the residual biomass potential in Germany consists of three components when viewed.

The data source related to grain straw potential in Germany comes from a research report from DBFZ [34]. Based on their research, the grain straw potential in Germany is about 16 million tons in total per year, and the distribution of potential spans across different municipalities [34]. These values have been integrated into the geographic information system and displayed on the agricultural areas. With the heat value of grain straw of 4.86 MWh/t [35], the total grain straw potential in Germany amounts to about 78 TWh_{th}/a.

When it comes to wood, according to the third Federal Forest Inventory, the total wood potential in Germany is about 204 TWh_{th}/a [36] This value will be evenly distributed within the forested areas of Germany using GIS software. The central and eastern regions exhibit relatively higher potential for residual wood resources. It is worth mentioning that the entire quantity cannot be exclusively allocated for TSPP power generation, as a portion of this potential is utilized for industrial purposes, such as furniture production, etc. However, due to the substantial magnitude of the total wood potential, Germany's wood resources greatly exceed the power generation demands of TSPPs, thereby ensuring no adverse impact on other industries.

The potential of urban organic waste is relatively small, about 6 TWh_{th}/a [34]. It comprises kitchen waste generated by citizens and leaves and branches from parks. Figure 11 has illustrated the PV potential and the three types of biomass potential for TSPP transformation in Germany.

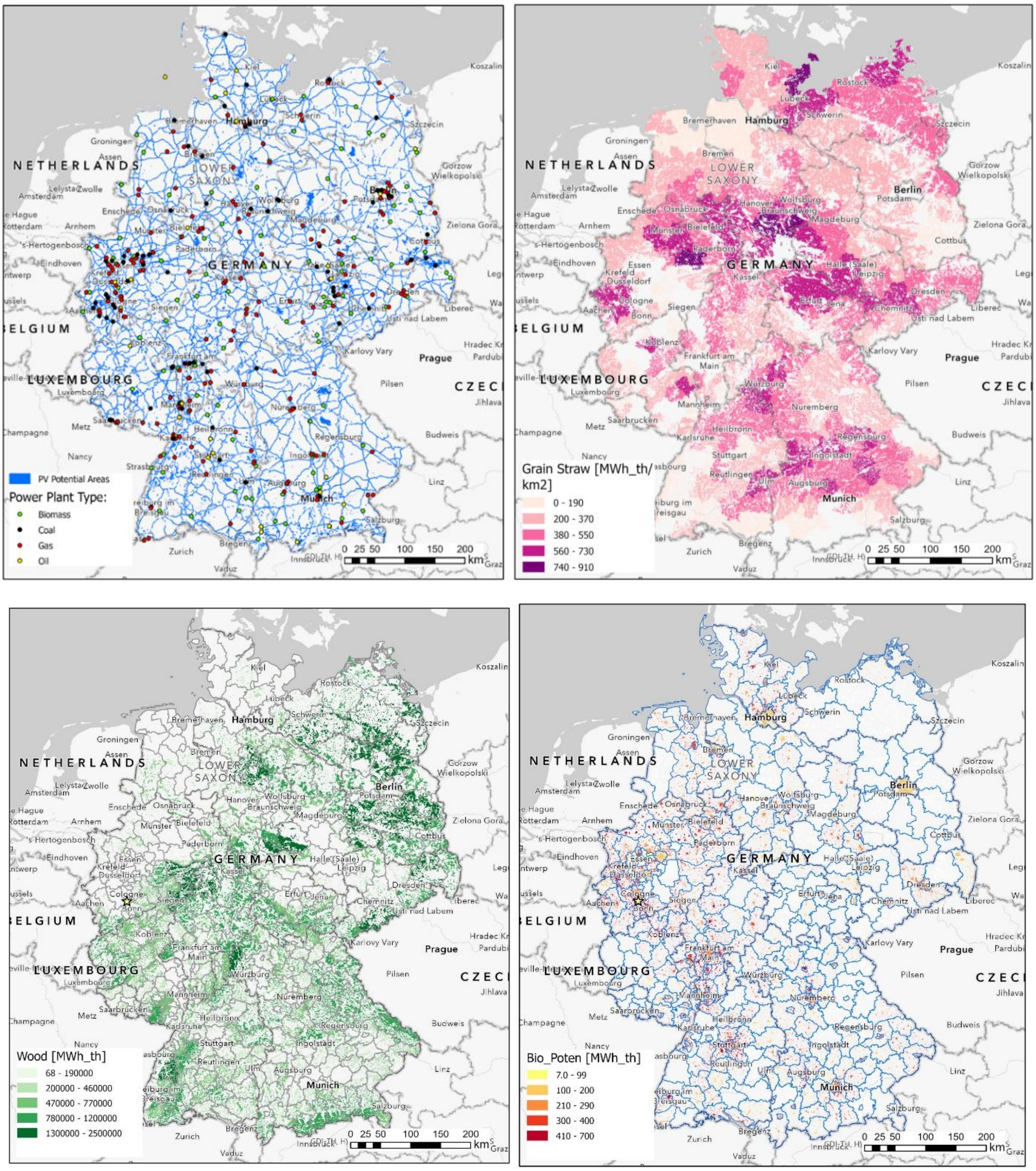

Figure 11: Total PV and biomass potential for TSPP in Germany. Above left: potential PV installation areas (marked as blue); Above right: residual grain straw potential (marked as pink); Bottom left: total wood potential in Germany (marked as green); Bottom right: total urban biowaste potential in Germany [23].

4.5 Establishing a TSPP-Atlas for Germany

After conducting the analysis using the method mentioned above, two types of transformation outcomes can be derived based on different transformation requirements:

The first type of outcome is approached from the perspective of macro-level decision-makers, emphasizing the overall transformation goals of a country. In this case, the ranking of individual power plants needs to be taken into consideration to ensure that, upon completion of the analysis, the most suitable power plants for transformation can access optimal PV and biomass resources. After the analysis, the installation of 70 GW of TSPP would require an area of 1547 km^2, which is approximately 0.4% of German total land area, considering the power plant ranking. When it comes to biomass consumption, the transformation process would take about 44.7 TWh_{th} of grain straw, which is roughly 50% of the annual grain straw potential. At the same time, 93.8 TWh_{th} of wood would be reserved for TSPP back-up, which is equivalent to about 46% of the total residual wood potential in Germany.

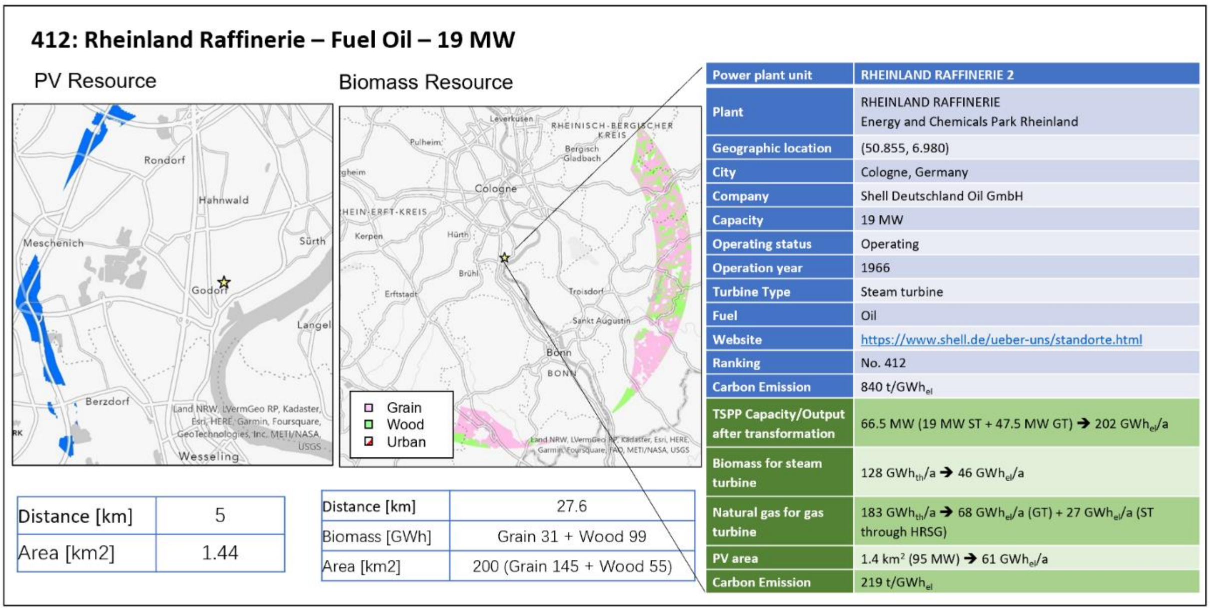

Figure 12: Data sheet of a TSPP with consideration of ranking criteria [21][23]

The second type of outcome is more approached from a practical perspective, analyzing the optimal transformation plan for a specific power plant from the viewpoint of a project manager. It focuses more on the specific power plant rather than the overall ranking. In practice, it is possible that a power plant with a lower ranking may be prioritized for transformation due to various reasons. In this case, the allocation of potential areas within the country follows a "first come, first served" principle.

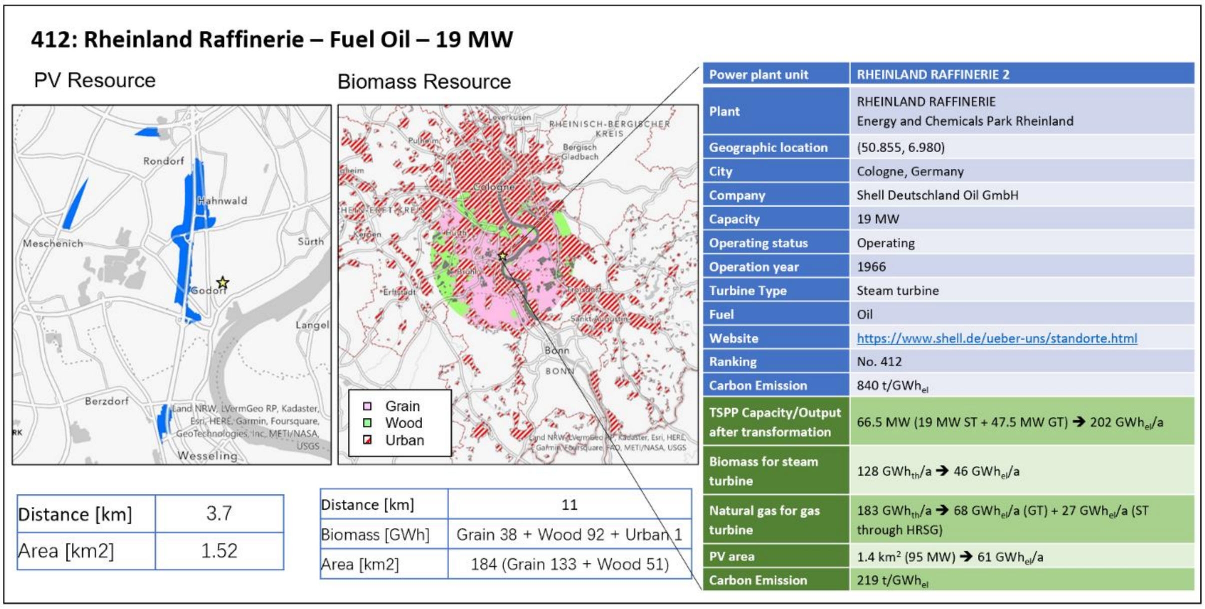

Figure 13: Data sheet of a TSPP without considering ranking [21][23].

The power plants depicted in Figure 12 and Figure 13 serve as examples to illustrate the two types of outcomes. This particular power plant has a relatively lower ranking, and when considering the ranking, the allocated areas it can obtain are relatively distant from the power plant. The complete analysis results encompass the transformation plans for all 70 GW of TSPPs, including their specific details, geographical locations, and the allocated PV and biomass resources.

The appendix provides examples of each type of power plant transformed into TSPP without considering their rankings. It is worth mentioning that the higher-ranked power plants are primarily biomass-based plants, and they already have stable biomass sources before the transformation, eliminating the need for additional analysis of biomass atlas. However, for academic purposes, new biomass maps and their sources are still provided for these power plants in the appendix, for reference.

5. Conclusion and outlook

This thesis at hand primarily investigates the transformation potential of TSPP in a specific country. Germany is used in this thesis as a case study, and the whole analysis of this TSPP transformation is based on the residual load from the demand side of about 213 TWh by 2040 and the transformation plan of 70 GW in total. The final research outcome is presented in the form of a TSPP atlas, which includes the overall potential for photovoltaic installations in Germany, along with their geographical locations. It also incorporates the overall residual biomass potential in Germany, along with potential locations for biomass acquisition. Additionally, the transformed TSPP are illustrated in detail in terms of their capacity, geographical locations, physical characteristics, and the corresponding geographical locations for photovoltaic installation and biomass integration. According to this transformation scenario, these TSPPs can meet the installation requirement of 70 GW and obtain the necessary photovoltaic and biomass resources in their vicinity. Except for increasing the capacity of energy storage systems and balancing the electricity surplus from the grid, the TSPP gives another solution from a power plant generation perspective when facing with the trend of energy transition. The comprehensive findings of the thesis in hand with three papers can be summarized as follows:

- In order to select the most suitable power plants from numerous conventional power plants for transformation into TSPP, this thesis introduces four evaluation criteria to score and rank these power plants. In future research, these evaluation criteria can be modified and supplemented based on the national conditions of different countries. For example, additional evaluation criteria could include greenhouse gas emissions during power generation or the additional costs resulting from the transformation. This would enable the most suitable power plants for transformation to achieve higher scores and rankings.
- Based on the calculation of the photovoltaic potential in Germany, the estimated potential area available for TSPP photovoltaic installations is approximately 15,000 km^2. This area can accommodate around 1,000 GW of photovoltaic capacity, far exceeding the required capacity of 105 GW for the transformation of TSPP. A significant portion of this area is derived from agricultural land along highways, which would require the implementation of Agri-PV for installation [25][26].

- In terms of biomass potential, Germany's biomass potential (including wood potential) is estimated to be around 300 TWh annually. In the TSPP transformation introduced in this thesis, approximately 145 TWh of biomass is ultimately utilized. This is primarily due to the TSPP configuration employed in this study, which incorporates natural gas as the fuel source for gas turbines, significantly reducing the demand for biomass in TSPP power generation. In the long term, natural gas could be substituted by biomethane, further increasing biomass demand.
- The final atlas is divided into two sections. Firstly, for the goal of transforming 70 GW of TSPP capacity, the thermal power plants are ranked according to a ranking criterion. Based on the ranking, the corresponding PV and biomass resources are allocated to each power plant. The second section focuses more on the individual transformation of each power plant, assigning theoretical optimal PV installation locations and biomass resource acquisition locations. From the results, it can be observed that the required resources for the entire 70 GW of TSPP capacity can be successfully obtained within the specified range.
- The economic analysis of TSPP transformation is determined by calculating the Levelized Cost of Electricity (LCOE) before and after the retrofit. By selecting four different types of power plants and calculating their respective LCOEs after being transformed into TSPPs, the following conclusions can be made: TSPPs can reduce the LCOE after transformation. Furthermore, TSPPs can significantly mitigate the negative impact of rising as well as the fluctuations of fossil fuel prices while reducing the use of fossil fuels and greenhouse gas emissions.
- In fact, the gas turbine in TSPP can be powered by 100% bioenergy. By converting biomass into biomethane, the gas turbine can be fueled completely by eliminating the reliance on fossil energy for TSPP operation. Currently, the efficiency of biomass conversion to biomethane is approximately 60%. Based on calculations, Germany's biomass potential (300 TWh) can still barely meet the demands of TSPP when 100% bioenergy is employed. Several methods can alleviate this situation: one is to mitigate the shortage of biomass by importing residual raw biomass from foreign countries, and another is to improve the efficiency of biomass conversion to biofuel. In the coming years, this efficiency is expected to reach more than 65%, which can mitigate the demand for residual biomass. The final method is to transform TSPP on a European scale. From a European perspective, the central and western regions have higher energy demands, but relatively limited

biomass potential, while the eastern regions have lower energy demands but vast agricultural land, thus presenting significant potential for residual biomass. If Europe is analyzed as a whole, the biomass potential easily exceeds the biomass required for TSPP transformation.

The TSPP transformation method described in this thesis is not only applicable to Germany but can also be applied to other countries. The difference lies in the varying renewable resources and significant geographical variations among countries. This method can be adapted after designing TSPP transformation scenario for different countries, and then utilize this approach to obtain the corresponding TSPP atlas.

For instance, in this thesis, the ratio between the capacity of the TSPP photovoltaic panels and the steam turbines in Germany is set at 5. This is because Germany's latitude is relatively high, and in order to achieve the required electricity generation from TSPP photovoltaic each year, it would require the installation of 105 GW of photovoltaic capacity. For other countries with better sunlight conditions, this ratio can be significantly reduced. For example, in regions with excellent sunlight conditions such as Northern Chile and North Africa, the ratio could be reduced to 3 or even 2, thereby substantially lowering the cost of TSPP transformation. The specific ratios for each country can be determined using the SolarGIS database [37].

In addition, the size proportions of different components in TSPPs can also be flexibly adjusted according to the different scenario. For example, in countries where there is abundant photovoltaic potential but relatively limited biomass potential, the installed capacity of photovoltaic systems in TSPPs can be increased appropriately. This would help reduce the TSPP's demand for biomass after the transformation. The specific adjustments can be made based on the specific situation of each country, and an evaluation can be derived through analysis using ELCALC based on multiple benchmarking criteria.

Based on the methods outlined in this dissertation, future analysis of other countries or the final creation of a global TSPP atlas faces the following challenges and areas for improvement:

- Global data availability: For countries outside the European Union, obtaining accurate and comprehensive data before the transformation might be challenging as some nations may lack specific and detailed landcover classifications, precise satellite imagery, time series of renewable power plants and detailed information on biomass availability and power plant distribution mentioned in this thesis. Establishing a detailed power plant database and clarifying land use in these countries could greatly enhance the feasibility and accuracy of TSPP analysis and planning.

- Policy and confidentiality regulations: Different countries have varying degrees of confidentiality regarding their geographic information, and some nations may withhold precise satellite maps or detailed power plant information due to national security considerations. When analyzing these countries, it is essential to collaborate with enterprises or governments through various channels to comply with their regulations and ensure the accuracy of TSPP analysis.
- Objective conditions of each country: When conducting transformations in certain countries, it is essential to consider various objective conditions specific to that nation. Factors such as changes in energy demand due to population dynamics over the coming decades, potential significant shifts in the country's long-term energy policies, and whether the country's economic conditions can accommodate the additional installation costs arising from the transformation need to be taken into account.

In spite of these challenges, TSPPs hold even greater significance for developing countries or industrial nations like China and other east Asia countries. These countries still face certain energy deficits to ensure normal and stable industrial production. Coal-fired power plants, being currently economically viable for electricity generation, remain among the options for new installation power plants in these countries. However, the TSPP approach adopted in this thesis can substantially reduce carbon emissions while ensuring an even more flexible and stable energy supply than the traditional thermal power plants. Additionally, since TSPPs can be newly constructed in these countries, it also helps in saving the costs associated with transforming old power plants. Therefore, TSPPs present a win-win solution for developing countries and countries in transition, providing both stable energy supply and significant reduction in carbon emissions.

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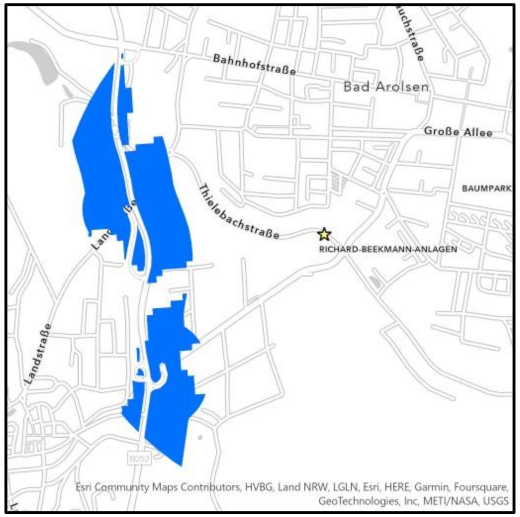
Appendix

Datasheets of 10 power plants in Germany as examples:

- 2 biomass power plants
- 2 combined cycle power plants
- 2 coal-fired power plants
- 2 oil-fired power plants
- 2 gas turbine power plants

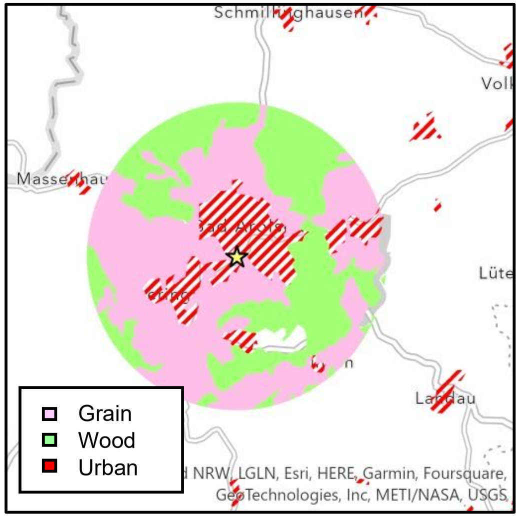
1: BAD AROLSEN BIOMASS 1 – Fuel Wood – 5.57 MW

PV Resource



Distance [km]	1.3
Area [km2]	0.44

Biomass Resource*



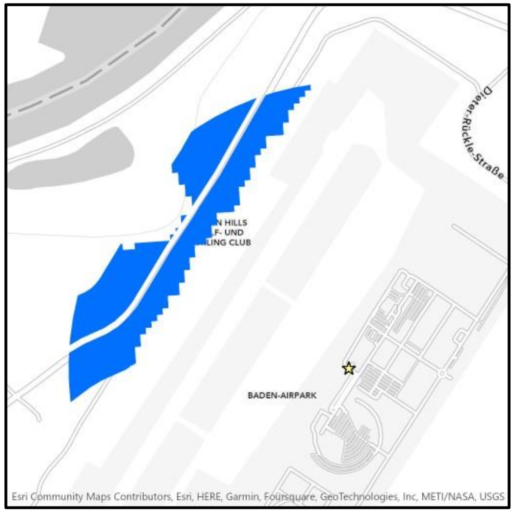
**:The biomass power plants already have stable biomass sources before transformation, so there is no need for additional biomass supply during the transformation. This picture is presented for academic purposes and theoretic analysis only.*

Distance [km]	3.8
Biomass [GWh]	Grain 8.5 + Wood 28.6 + Urban 0.3
Area [km2]	38 (Grain 22 + Wood 16)

Power plant unit	BAD AROLSEN BIOMASS 1
Plant	BAD AROLSEN BIOMASS
Geographic location	(51.374, 9.009)
City	Bad Arolsen, Germany
Company	BAYERNFONDS BESTENERGY 1 GMBH
Capacity	5.57 MW
Operating status	Operating
Operation year	2009
Turbine Type	Steam turbine
Fuel	Wood
Website	https://blue -energy-group.de/bioenergiepark -bad-arolsen/
Ranking	Nr. 1
Carbon Emission	0 t/GWh_{el}
TSPP Capacity/Output after transformation	19.5 MW (5.57 MW ST + 13.93 MW GT) ➔ 59 GWh_{el}/a
Biomass for steam turbine	37 GWh_{th}/a ➔ 13 GWh_{el}/a
Natural gas for gas turbine	54 GWh_{th}/a ➔ 20 GWh_{el}/a (GT) + 8 GWh_{el}/a (ST through HRSG)
PV area	0.44 km^2 (28 MW) ➔ 18 GWh_{el}/a
Carbon Emission	220 t/GWh_{el}

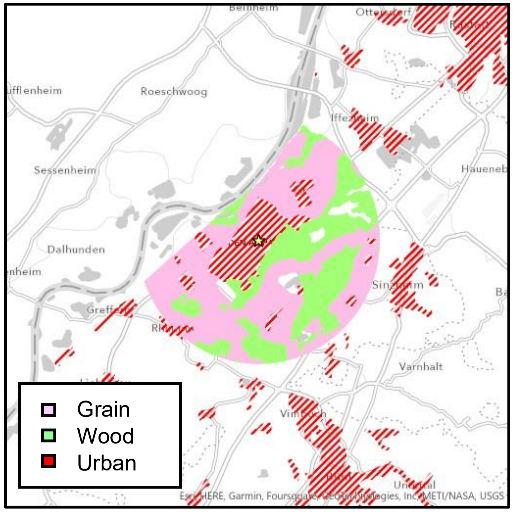
2: BADEN-AIRPARK 1 – Fuel Wood – 5.2 MW

PV Resource



Distance [km]	1.4
Area [km2]	0.44

Biomass Resource*



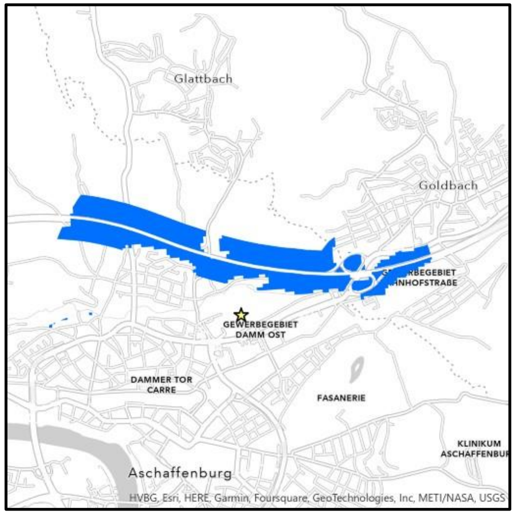
**:The biomass power plants already have stable biomass sources before transformation, so there is no need for additional biomass supply during the transformation. This picture is presented for academic purposes and theoretic analysis only.*

Distance [km]	4.9
Biomass [GWh]	Grain 4.6 + Wood 30 + Urban 0.3
Area [km2]	45 (Grain 28 + Wood 17)

Power plant unit	BADEN-AIRPARK 1
Plant	BADEN-AIRPARK
Geographic location	(48.779, 8.088)
City	Baden-Baden, Germany
Company	STADTWERKE BADEN -BADEN
Capacity	5.2 MW
Operating status	Operating
Operation year	2006
Turbine Type	Steam turbine
Fuel	Wood
Website	https://www.baden -airpark.de/
Ranking	Nr. 2
Carbon Emission	0 t/GWh_{el}
TSPP Capacity/Output after transformation	18.2 MW (5.2 MW ST + 13 MW GT) → 55 GWh_{el}/a
Biomass for steam turbine	35 GWh_{th}/a → 13 GWh_{el}/a
Natural gas for gas turbine	50 GWh_{th}/a → 19 GWh_{el}/a (GT) + 7 GWh_{el}/a (ST through HRSG)
PV area	0.39 km^2 (26 MW) → 16 GWh_{el}/a
Carbon Emission	220 t/GWh_{el}

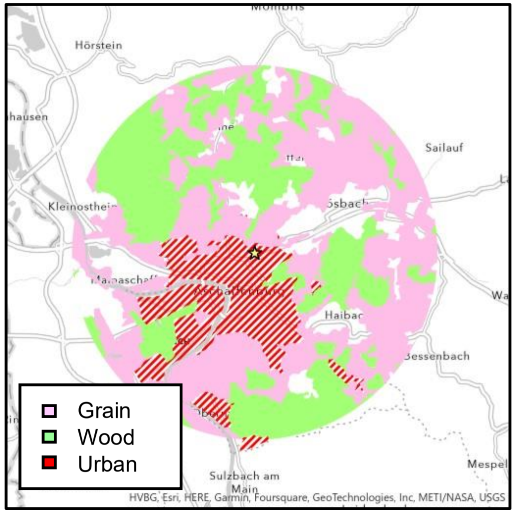
70: ASCHAFFENBURG MILL CC – Fuel Gas – 48 MW

PV Resource



Distance [km]	1.9
Area [km2]	1.2

Biomass Resource

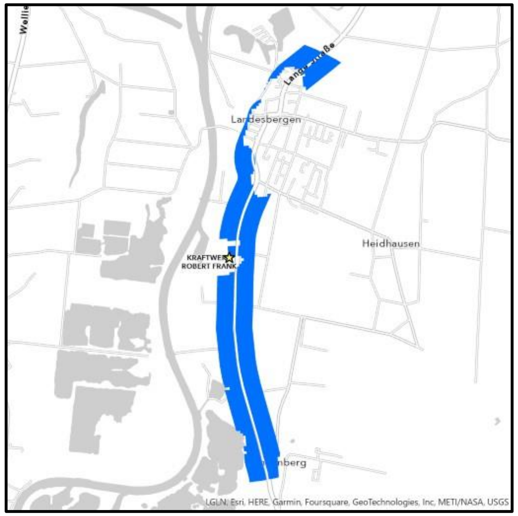


Distance [km]	7
Biomass [GWh]	Grain 19 + Wood 89 + Urban 0.5
Area [km2]	93 (Grain 47 + Wood 46)

Power plant unit	ASCHAFFENBURG MILL CC
Plant	ASCHAFFENBURG MILL
Geographic location	(49.98771, 9.15505)
City	Aschaffenburg, Germany
Company	DS SMITH PAPER DEUTSCHLAND
Capacity	48 MW
Operating status	Operating
Operation year	2013
Turbine Type	Combined Cycle
Fuel	Gas
Website	https://www.dssmith.com/company/locations/our - paper-mills/aschaffenburg -paper-mill
Ranking	Nr. 70
Carbon Emission	456 t/GWh_{el}
TSPP Capacity/Output after transformation	48 MW (16 MW ST + 32 MW GT) ➔ 149 GWh_{el}/a
Biomass for steam turbine	108 GWh_{th}/a ➔ 39 GWh_{el}/a
Natural gas for gas turbine	99 GWh_{th}/a ➔ 37 GWh_{el}/a (GT) + 23 GWh_{el}/a (ST through HRSG)
PV area	1.2 km^2 (90 MW) ➔ 51 GWh_{el}/a
Carbon Emission	160 t/GWh_{el}

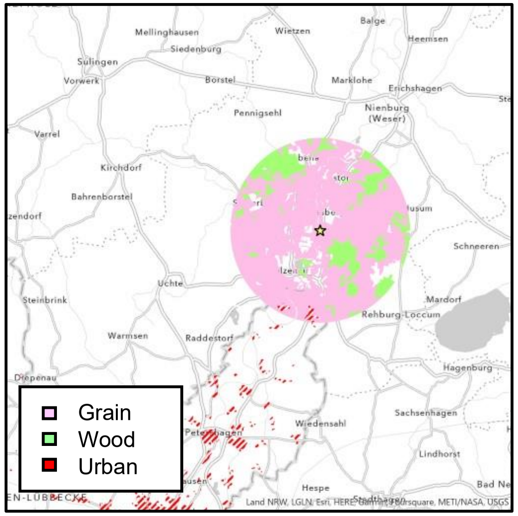
77: BRAUNSCHWEIG MITTE CC – Fuel Gas – 76 MW

PV Resource



Distance [km]	2.6
Area [km2]	1.91

Biomass Resource

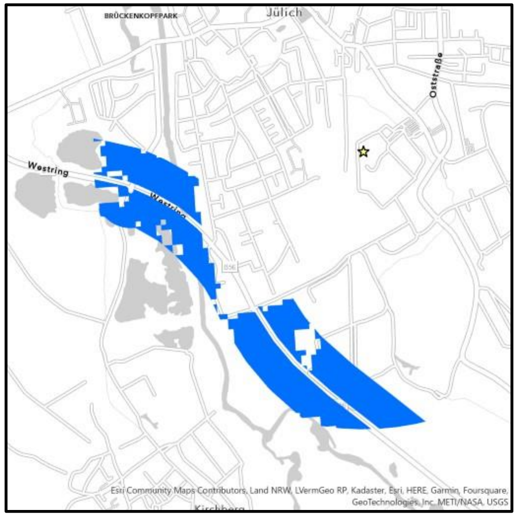


Distance [km]	4.9
Biomass [GWh]	Grain 90 + Wood 80 + Urban 0.2
Area [km2]	204 (Grain 169 + Wood 35)

Power plant unit	BRAUNSCHWEIG MITTE CC
Plant	BRAUNSCHWEIG MITTE
Geographic location	(52.27876, 10.515)
City	Braunschweig, Germany
Company	BS ENERGY-BRAUNSCHWEIGER VER
Capacity	76 MW
Operating status	Operating
Operation year	2010
Turbine Type	Combined Cycle
Fuel	Gas
Website	https://www.bs-energy.de/unternehmen/versorgung/erzeugungsanlagen/
Ranking	Nr. 77
Carbon Emission	456 t/GWh_{el}
TSPP Capacity/Output after transformation	76 MW (25.3 MW ST + 50.6 MW GT) → 236 GWh_{el}/a
Biomass for steam turbine	170 GWh_{th}/a → 61 GWh_{el}/a
Natural gas for gas turbine	156 GWh_{th}/a → 58 GWh_{el}/a (GT) + 36 GWh_{el}/a (ST through HRSG)
PV area	1.9 km^2 (127 MW) → 81 GWh_{el}/a
Carbon Emission	160 t/GWh_{el}

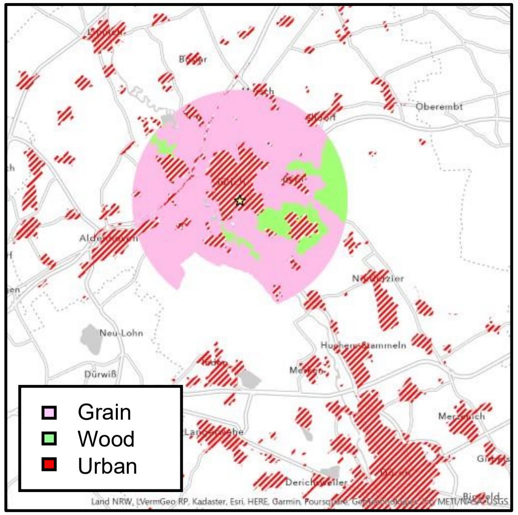
106: JULICH SUGAR 2 – Fuel Coal – 25.5 MW

PV Resource



Distance [km]	1.6
Area [km2]	0.62

Biomass Resource



Distance [km]	5.1
Biomass [GWh]	Grain 35 + Wood 15 + Urban 0.3
Area [km2]	62 (Grain 53 + Wood 9)

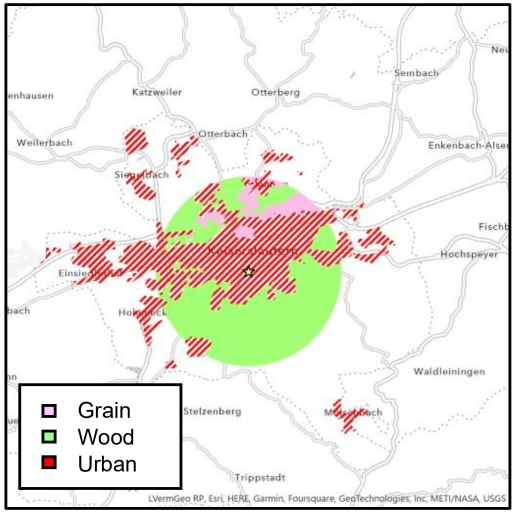
Power plant unit	JULICH SUGAR 2
Plant	JULICH SUGAR
Geographic location	(50.91458, 6.36943)
City	Julich - Duren, Germany
Company	ZUCKERFABRIK JULICH AG
Capacity	25.5 MW
Operating status	Operating
Operation year	2004
Turbine Type	Steam turbine
Fuel	Coal
Website	https://www.pfeifer-langen.com/de/unternehmen/standorte/juelich/
Ranking	Nr. 106
Carbon Emission	850 t/GWh_{el}
TSPP Capacity/Output after transformation	25.5 MW (7.3 MW ST + 18.2 MW GT) ➔ 77 GWh_{el}/a
Biomass for steam turbine	49 GWh_{th}/a ➔ 18 GWh_{el}/a
Natural gas for gas turbine	70 GWh_{th}/a ➔ 26 GWh_{el}/a (GT) + 10 GWh_{el}/a (ST through HRSG)
PV area	0.55 km^2 (37 MW) ➔ 24 GWh_{el}/a
Carbon Emission	219 t/GWh_{el}

107: KARCHERSTRASSE 4 – Fuel Coal – 7.2 MW

PV Resource

Distance [km]	2.7
Area [km2]	0.59

Biomass Resource

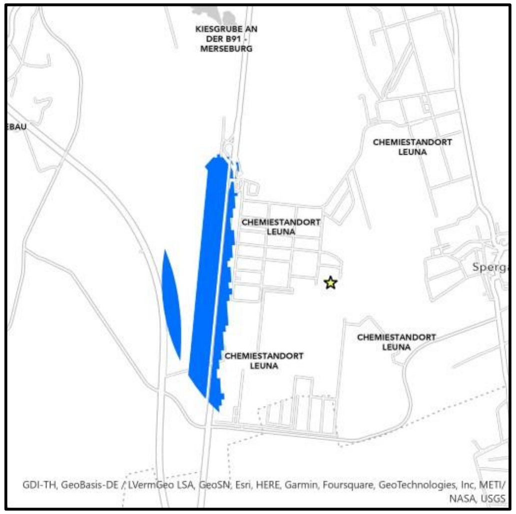


Distance [km]	4.1
Biomass [GWh]	Grain 1 + Wood 49 + Urban 0.2
Area [km2]	31 (Grain 3 + Wood 28)

Power plant unit	KARCHERSTRASSE 4
Plant	KARCHERSTRASSE
Geographic location	(49.43457, 7.75834)
City	Kaiserslautern, Germany
Company	SWK STADTWERKE KAISERSLAUTERN
Capacity	7.2 MW
Operating status	Operating
Operation year	2009
Turbine Type	Steam turbine
Fuel	Coal
Website	https://www.gem.wiki/Karcherstra%C3%9Fe_power_station
Ranking	Nr. 107
Carbon Emission	850 t/GWh$_{el}$
TSPP Capacity/Output after transformation	25.2 MW (7.2 MW ST + 18 MW GT) ➔ 76 GWh$_{el}$/a
Biomass for steam turbine	48 GWh$_{th}$/a ➔ 17 GWh$_{el}$/a
Natural gas for gas turbine	69 GWh$_{th}$/a ➔ 26 GWh$_{el}$/a (GT) + 10 GWh$_{el}$/a (ST through HRSG)
PV area	0.54 km^2 (36 MW) ➔ 23 GWh$_{el}$/a
Carbon Emission	220 t/GWh$_{el}$

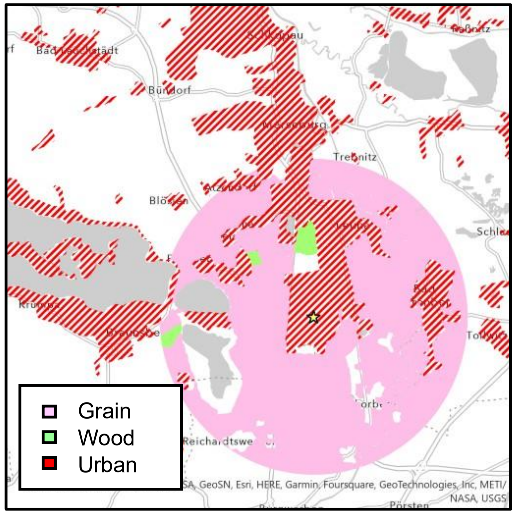
229: LEUNA REFINERY S1 – Fuel Oil – 29.5 MW

PV Resource



Distance [km]	1.7
Area [km2]	0.77

Biomass Resource

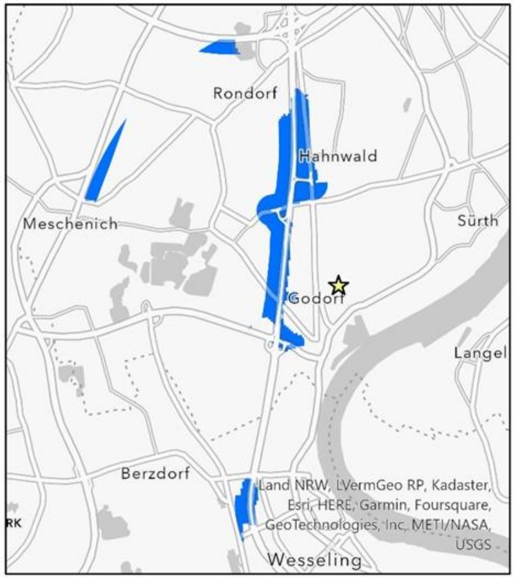


Distance [km]	6.2
Biomass [GWh]	Grain 54 + Wood 2.8 + Urban 0.1
Area [km2]	82 (Grain 80 + Wood 1.6)

Power plant unit	LEUNA REFINERY S1
Plant	LEUNA REFINERY
Geographic location	(51.29178, 11.99977)
City	Leuna, Germany
Company	STEAG GMBH
Capacity	29.5 MW
Operating status	Operating
Operation year	1994
Turbine Type	Steam turbine
Fuel	Oil
Website	https://energy -oil-gas.com/news/total-refinery-leuna/
Ranking	Nr. 229
Carbon Emission	840 t/GWh_{el}
TSPP Capacity/Output after transformation	29.5 MW (8.4 MW ST + 21.1 MW GT) ➔ 89 GWh_{el}/a
Biomass for steam turbine	56 GWh_{th}/a ➔ 20 GWh_{el}/a
Natural gas for gas turbine	82 GWh_{th}/a ➔ 30 GWh_{el}/a (GT) + 12 GWh_{el}/a (ST through HRSG)
PV area	0.63 km^2 (42 MW) ➔ 27 GWh_{el}/a
Carbon Emission	221 t/Gwh_{el}

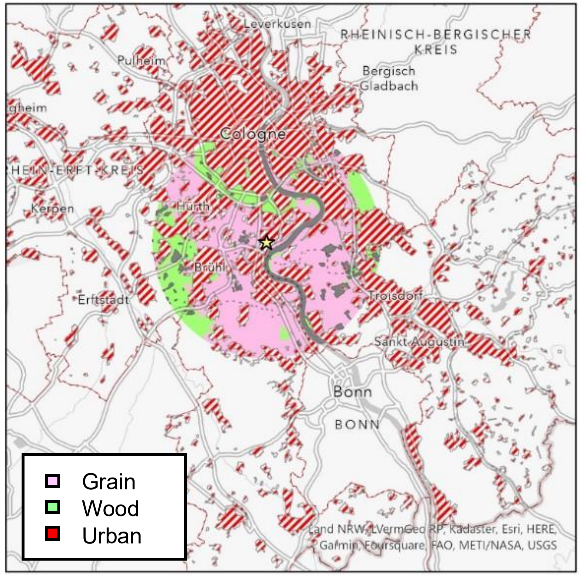
412: Rheinland Raffinerie – Fuel Oil – 19 MW

PV Resource



Distance [km]	3.7
Area [km2]	1.52

Biomass Resource

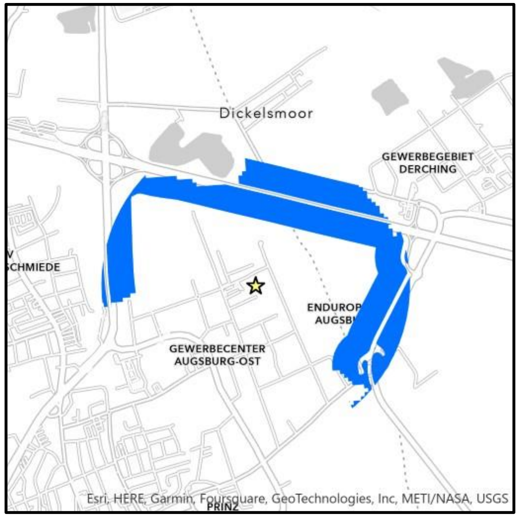


Distance [km]	11
Biomass [GWh]	Grain 38 + Wood 92 + Urban 1
Area [km2]	184 (Grain 133 + Wood 51)

Power plant unit	RHEINLAND RAFFINERIE 2
Plant	RHEINLAND RAFFINERIE Energy and Chemicals Park Rheinland
Geographic location	(50.855, 6.980)
City	Cologne, Germany
Company	Shell Deutschland Oil GmbH
Capacity	19 MW
Operating status	Operating
Operation year	1966
Turbine Type	Steam turbine
Fuel	Oil
Website	https://www.shell.de/ueber -uns/standorte.html
Ranking	No. 412
Carbon Emission	840 t/GWh_{el}
TSPP Capacity/Output after transformation	66.5 MW (19 MW ST + 47.5 MW GT) ➔ 202 GWh_{el}/a
Biomass for steam turbine	128 GWh_{th}/a ➔ 46 GWh_{el}/a
Natural gas for gas turbine	183 GWh_{th}/a ➔ 68 GWh_{el}/a (GT) + 27 GWh_{el}/a (ST through HRSG)
PV area	1.4 km^2 (95 MW) ➔ 61 GWh_{el}/a
Carbon Emission	219 t/GWh_{el}

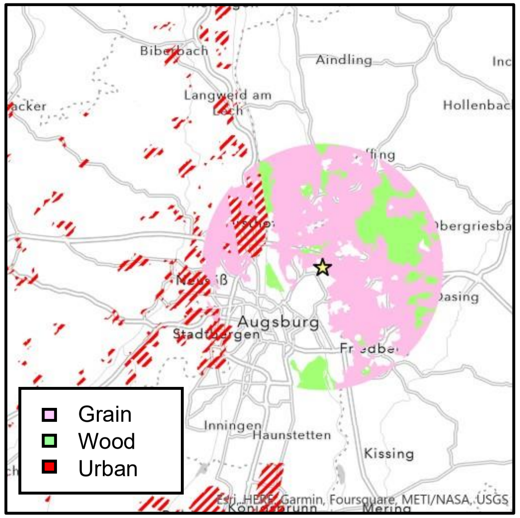
155: AUGSBURG OST GT 1 – Fuel Gas – 30 MW

PV Resource



Distance [km]	1.2
Area [km2]	1.06

Biomass Resource

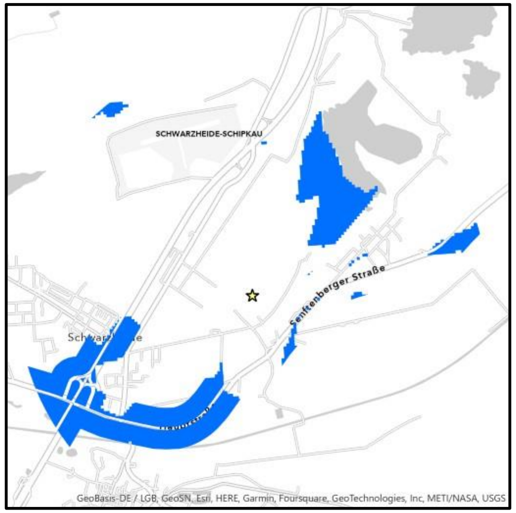


Distance [km]	7.5
Biomass [GWh]	Grain 39 + Wood 41 + Urban 0.4
Area [km2]	95 (Grain 73 + Wood 22)

Power plant unit	AUGSBURG OST GT 1
Plant	AUGSBURG OST GT
Geographic location	(48.40099, 10.93576)
City	Augsburg, Germany
Company	STADTWERKE AUGSBURG HOLDING
Capacity	30 MW
Operating status	Operating
Operation year	2005
Turbine Type	Gas turbine
Fuel	Natural Gas
Website	https://www.sw-augsburg.de/
Ranking	Nr. 155
Carbon Emission	711 t/GWh$_{el}$
TSPP Capacity/Output after transformation	42 MW (12 MW ST + 30 MW GT) ➔ 127 GWh$_{el}$/a
Biomass for steam turbine	81 GWh$_{th}$/a ➔ 29 GWh$_{el}$/a
Natural gas for gas turbine	116 GWh$_{th}$/a ➔ 43 GWh$_{el}$/a (GT) + 17 GWh$_{el}$/a (ST through HRSG)
PV area	0.9 km^2 (60 MW) ➔ 39 GWh$_{el}$/a
Carbon Emission	220 t/GWh$_{el}$

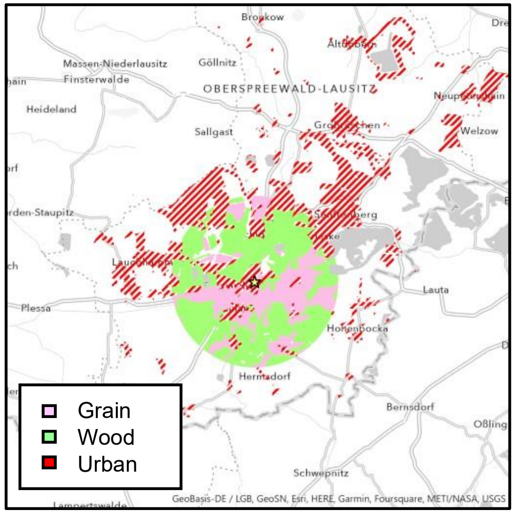
159: BASF SCHWARZHEIDE GT 1RP – Fuel Gas – 57 MW

PV Resource



Distance [km]	2.5
Area [km2]	1.76

Biomass Resource



Distance [km]	7.1
Biomass [GWh]	Grain 7.7 + Wood 147
Area [km2]	124 (Grain 42 + Wood 82)

Power plant unit	BASF SCHWARZHEIDE GT 1RP
Plant	BASF SCHWARZHEIDE
Geographic location	(51.4762, 13.8891)
City	Schwarzheide - Oberspreewald -Lausitz, Germany
Company	BASF AG
Capacity	57 MW
Operating status	Operating
Operation year	2021
Turbine Type	Gas turbine
Fuel	Natural Gas
Website	https://www.basf.com/global/de/who -we-are/organization/locations/europe/german -sites/Schwarzheide.html
Ranking	Nr. 159
Carbon Emission	711 t/GWh_{el}
TSPP Capacity/Output after transformation	79.8 MW (22.8 MW ST + 57 MW GT) ➔ 242 GWh_{el}/a
Biomass for steam turbine	153 GWh_{th}/a ➔ 55 GWh_{el}/a
Natural gas for gas turbine	220 GWh_{th}/a ➔ 81 GWh_{el}/a (GT) + 33 GWh_{el}/a (ST through HRSG)
PV area	1.71 km^2 (114 MW) ➔ 73 GWh_{el}/a
Carbon Emission	220 t/GWh_{el}