Report

An approach to reducing the greenhouse gas footprint in the manufacturing industry:

Determinants for an economic assessment of industrial decarbonisation measures

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Abstract: A reduction of the greenhouse gas footprint towards net zero emissions can be achieved with the help of a wide variety of measures. There are three principal approaches (categories): first, reducing greenhouse gases by adjusting the way business is done (efficiency and processes); second, substituting what business is done with (sources of energy and material); and third, offsetting the greenhouse gases emitted.

Some measures seem simple and obvious, while others appear complex and demanding. The decisive factor is the respective impact on economic efficiency. Therefore, the authors have identified six types of measures that differ in terms of the impact of investment and operating costs on energy and emission costs.

In this report, the authors evaluate these types of measures from an economic perspective and address the limitations and advantages and disadvantages of the different types of measures in terms of emerging needs for action and consequences. Since, for example, on-site measures are often more sensible and also the increase or introduction of emission prices in many countries can have significant cost implications (and subsequently affect global supply chains), an adjustment of the traditional approach to economic valuation seems necessary.

On this basis, a novel economic valuation approach for decarbonisation measures is proposed. The approach, illustrated by calculation examples and extensions to dynamically rank, score, and adjust to changing circumstance over time, facilitates an optimal selection of measures to support companies in achieving and sustaining their greenhouse gas reduction goals while maintaining economic efficiency.

Keywords: economic viability, opportunity costs, decarbonisation, economic assessment, net-zero emissions, energy efficiency, renewable energy, emission compensation, industry, decarbonisation measures

Disclaimer: This is an update, adaptation and extension of S. M. Büttner, D. Wang, C. Schneider, "Der Weg zur Klimaneutralität - Bausteine einer neuen Methodik zur Bestimmung eines wirtschaftlichen Maßnahmenmix" [1] to the international context, and in such the foundation of ECE/ENERGY/GE.6/2021/3 [2] and GEEE-8/2021/INF.2 [3].

1. Introduction

1.1 Clarity in terminology and its meaning, as well as targets is essential

The foundation for finding an economic mix of measures to achieve net zero is, on the one hand, clarity about the point in time by which this target should be achieved and, on the other hand, about whether there are ideational or structural limitations on the available instruments [4]. Moreover, it is particularly significant to establish absolute clarity about the terminologies and ensure a mutual understanding of these among all actors involved in the process [5]. A certain state (e.g., Scope 3 carbon neutrality) can be achieved however efficiently - this efficiency is worthless if the required outcome is a different one (e.g., Scope 1+2 climate neutrality). One would have tackled aspects unnecessary for the goal (here: extending to Scope 3 emissions) and, at the same time, neglected to address other aspects that would have been necessary for achieving the goal (here: addressing greenhouse gases apart from CO_2, such as methane). This also applies to net zero goals and the way to achieve them. The following example represents no rarity and underlines an insufficient clarity: in late 2020, the *New York Times* reported that Japan's new government has set itself the goal of *carbon* neutrality. At the same time, the *Reuters* reports that Japan is now striving for *climate* neutrality, showing a discrepancy in reported target dimensions [6,7].

Possibly decisive in this frequent confusion is that greenhouse gases (GHG, including CO_2 itself), whose mitigation make *climate* neutrality reachable, are measured in the unit "CO_2 equivalents". The suffix "-eq" for "equivalents" (CO_2-eq) is then quickly lost in common usage, resulting in "just" CO_2 with the corresponding CO_2 neutrality as target dimension [5].

Actual and complete neutrality - be it CO_2-, climate-, or environmental neutrality (cf**. Figure 1**) – is hardly achievable. In most cases it can only be achieved regarding the 'bottom line', this is 'net-zero'.

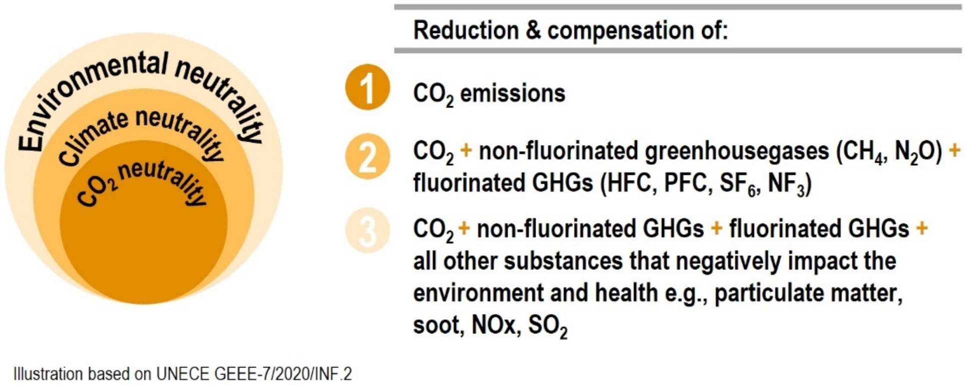

Figure 1. Defining different neutralities and what is needed to achieve them [5]

The situation is not much different when it comes to identifying the emissions footprint. Which emissions count, and which ones do not? Is climate neutrality defined as achieving net-zero greenhouse gas (GHG) emissions based on local emissions from one's site and the purchase of energy from climate-neutral sources? Or does the GHG footprint also include emissions emitted by employees on the way to their workplace, by business travel and by logistics, such as transporting materials to the factory and the finished products to their customers? Does climate neutrality mean the end product itself has a "net zero greenhouse gas emissions" footprint at the "point of handover" to the end customer - i.e., a full decarbonisation including the upstream and downstream supply chain? Or would climate neutrality be only achieved if all lifetime emissions (including disassembly and recycling) of a product are included in the calculations?

How stakeholders define their 'system boundaries' for decarbonisation activities also determines which "Scope" or which elements of this "Scope" they work towards. Scope 1+2 are often aspects under direct control of companies, Scope 3 are indirect emissions and often more difficult to capture and address (cf. **Figure 2**) [8].

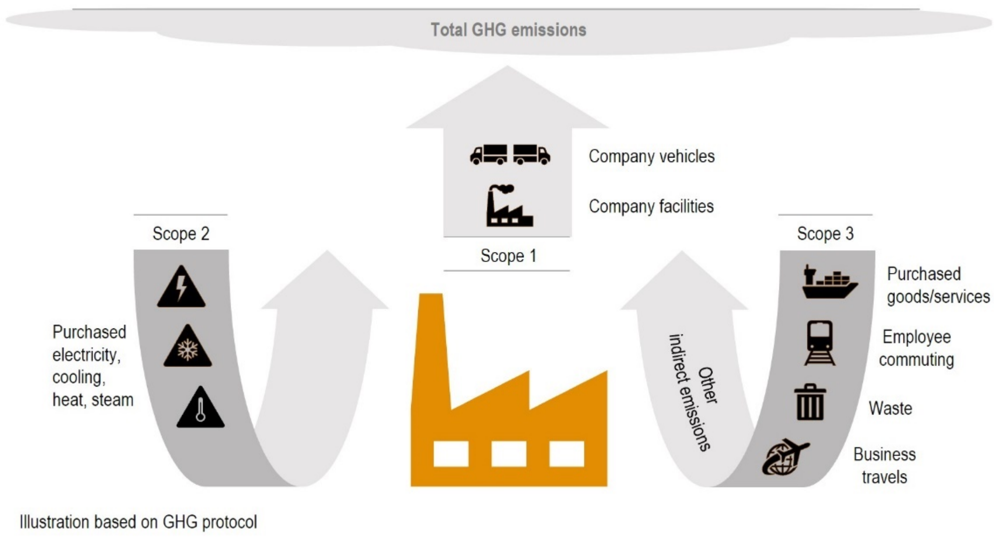

Figure 2. Carbon footprint assessment Scopes based on the GHG protocol [8]

Legislative initiatives by the European Union and individual member states (e.g., supply chain regulation and sustainable product initiative) [9,10] as well as announcements by car manufacturers and suppliers indicate a trend towards climate neutrality at the "point of handover" in this part of the world. The point of handover refers to the time when the end customer receives the product or places the item into their shopping cart after paying at the checkout [11].

Therefore, as target dimension, target scope and how they are understood can also vary across the world, across stakeholders and often within individual stakeholders, a common understanding needs to be established initially, and a clear (minimal) objective must be determined, considering one's values and external factors before proceeding further [12].

In addition, there are other relevant definitions for which a common understanding among decision-makers is mandatory, among others: energy-related emissions and process-related emissions. On the one hand, energy-related emissions occur when primary energy (raw fuels) is converted into a secondary energy carrier e.g., electricity, which can for example then be used to power a LED bulb that produces 800 lumens of brightness with consuming energy at a rate of 5 Watts per hour. On the other hand, process emissions emerge during the production process, such as by-products of chemical reactions or livestock breeding (e.g., methane emission from cattle).

1.2 Awareness of own emission footprint, requirements and regulations

Determining energy-related emissions is simple if data on the consumption per energy source and its composition (electricity mix) are available, which can be multiplied by the corresponding "emission factor" [13,14].[1] Conversely, it is much more challenging to determine process-related emissions. Firstly, there is a risk of misunderstanding: process-related emissions are often misunderstood as the energy-related emissions of a process. Secondly, actual process-related emissions are more difficult to measure (accurately) and, apart from sectors with large amounts of process emissions, may be hardly noticeable or not known to exist. Conversely, companies that have to report (and pay for) their process-related emissions are more likely to also know the energy-related footprint of their activities for two reasons: First, energy-related emissions should be comparatively easy for them to determine and, second, in the case of electricity, they are often already factored into the price of energy charged by energy suppliers and hence a noticeable cost-driver [15]

It is also indispensable to be familiar with (where applicable) the national- [16], the European- [17], or other regional emission pricing systems and whether the applicable pricing system explicitly includes all greenhouse gas emissions (CO_2 equivalents) or only CO_2. It is

[1] Some chambers of commerce offer calculators to determine CO_2-costs for energy related emissions, i.e. IHK CO_2-Calculator [14].

also important to know whether it applies to both energy and process-related emissions, or only to energy-related emissions, or whether this depends on the industrial sector.[2]

1.3 Three categories of measures to address the emissions footprint

In the following, we address emissions that are primarily under the direct control of decision-makers in the company. To address these, three principal categories of decarbonisation measures are defined:

- Reduction of greenhouse gases by adapting *how* one does business (efficiency and processes)
- Substitution of *what* one does business with (energy sources and materials)
- Offsetting the greenhouse gases emitted.

Substitution can be seen as an “upstream” emissions mitigation (preventing emissions from occurring), while offsetting can be seen as “downstream”.

Based on this definition, we performed a combined consideration of economic and energy aspects. Since both long-term effect and dependence on external factors are taken into account, these categories of decarbonisation measures are suitable as indicator categories for corporate management on the path to climate neutrality [18,19].

1.4 Why a novel approach is needed for decarbonisation: Gap, Relevance and Methodology

Which measures are actually implemented depends on a number of aspects. In particular, spatial, technical or strategic aspects can lead to a pre-selection or exclusion of some possible measures. After this pre-selection, in the vast majority of cases the financial aspects are in the foreground, such as the question within which period of time the measure will pay off.

In practice, measures are often only implemented if they pay off in a short period of time, usually no more than 3 years. In view of unclear planning horizons, economic cycles and product cycles, this is understandable. Nevertheless, it can still lead to some (very) worthwhile measures being excluded from the outset or to measures that are worthwhile in the short-term turning out to be a cost or resilience risk in the medium to long term.

Regarding production, on the *micro level* the time in which one will probably be able to produce a product with this equipment is defined more by the product cycles (cf. mobile phones, computer chips) than by the technical durability of the production equipment, and the risks mentioned might be overlooked in this micro perspective.
However, this is different for measures on the *meso- or macro level*. With few exceptions, decarbonisation targets are set for the medium to long term and exceed the 3-year time horizon, which is usually applied. Nonetheless, in many cases the “traditional” payback time methodology is still applied, although it would be economically more efficient to optimise for the year of the (intermediate) target (taking into account the sometimes shorter “useful lives” of some components and plants).
Above all, the many crises that mark our time show that there can be noticeable consequences if the costs of non-action, availability barriers and price risks for energy and possibly emission prices are not taken into account.

Since the established procedures do not address these aspects sufficiently, this report focuses on providing decision-makers in companies, service providers, financiers of politics, but also households with a methodology/an approach that addresses the shortcomings described and that they can use to determine their optimal mix of measures. The latter must make economic sense for their objectives, regardless of which country they are in, what the energy prices are there or whether there are emission levies.

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[2] i.e., in the German *National Emissions Trading System* [16] all sources of energy which lead to CO_2-Emissions and are not falling under EU ETS jurisdiction are considered. The EU Emissions Trading System EU ETS [17] covers CO_2 from electricity & heat generation, energy-intensive industry sectors and commercial aviation within the European Economic Area, N_2O & fluorinated GHGs.

To this end, the report first provides an insight into the importance of definitions in order to avoid misunderstandings. Then it elaborates on the impact of the three main types of measures and their subcategories, before further explaining how external effects can have a massive positive or negative impact. Taking these factors into account, a new calculation system that takes the above aspects into account is developed and presented.

Finally, an outlook is given on how this can be embedded in the wider decision-making context and how it can be simplified and dynamically adapted to constantly changing circumstances through digital measures, resulting in the optimal mix of measures for each chosen point in time.

2. Six types of measures and their impact

The three basic categories need to be further subdivided and then evaluated in terms of their *general* impact to allow derivations for the determination of an economic mix of measures. For each type of measure, both the *one-off economic effect* and the *permanent economic effect* are assessed, as well as whether it has a direct *impact on emissions*.

2.1 Reduction

The category “reduction” includes types of measures that - regardless of the energy source - lead to a reduction in emissions. This can be achieved in various ways:

Measure type 1: Reduction of energy consumption

The (final) energy consumption can be reduced through a variety of selective (i.e., increasing the energy efficiency of a paint shop) or systemic measures (i.e., increasing efficiency of the compressed air system or energy management system) without negatively affecting the production quantity or quality. With these measures, known as energy efficiency measures, the desired result is achieved with less energy input, meaning that more value is obtained from one unit of energy.

Economic one-off effect: The implementation of energy efficiency measures requires various one-off interventions, depending on the type of measure: in most cases, these are *one-off investments* for the purchase of more efficient products, machinery and equipment and, if necessary, for their selection and installation. However, *organisational* and *awareness-raising measures* (e.g., switching off lamps or appliances that are not needed) and the *optimised use of existing control systems* (e.g., heating control) can also achieve relevant savings *without investing* in hardware. This activity can increase energy efficiency as well as uncover and eliminate energy wastage. Nevertheless, one-off time resources or external support are required. If monitoring is desired, additional costs are incurred for mobile or stationary measuring devices, for example, thermal imaging cameras, which can use artificial intelligence to automatically detect and report leaks in compressed air systems at comparatively low cost [20].

Lasting effect: The lasting effect of type 1 measures (reduction of energy consumption) is that the amount of energy required for a unit of output, i.e., ongoing energy costs, falls permanently to a lower level. This also increases energy productivity (revenue generated per unit of energy used). The higher the energy cost share of a product, the greater the positive impact of energy efficiency improvements on energy productivity and competitiveness. The energy costs saved could, for example, be used to reduce the end-customer price, refinance investments, increase the profit margin, create or maintain jobs, or a combination of these measures.
It should be noted that systemic optimisation often involves measures that go beyond the energetic 1:1 optimisation of the initial state. For example, the installation of brightness sensors that switch the lighting on and off independently depending on the incidence of light or also regulate the power independently so that the brightness is always maintained at a certain level, taking into account the brightness of natural light. If a higher brightness (lumens per square metre) is selected when light sources are replaced, for example to improve working conditions or (work) safety, or if larger or additional equipment is purchased, some of the

savings are eaten up again. This is called the *rebound effect* [21], which however is not subject of this study.

Conclusion: Reducing the amount of energy required to achieve a certain output not only leads to *lower ongoing energy costs* but also a *reduction in ongoing (energy-related) emissions* to the same extent (unless the energy source is already emission-free).

Measure type 2: Reduction of process-related emissions

Reducing process-related emissions is often only possible through a fundamental adjustment of the production process itself, a change in the form of energy required for the process, or a combination of these measures. An example of this can be found in steel production, where iron ore and coke are traditionally combined at high temperatures. The cast iron created in this reaction through incorporation of carbon atoms (C) from the coke is, in a further step, injected with oxygen (O_2) to remove the carbon (C) in the form of CO_2 and obtain steel [22]. This result can also be achieved by other means, e.g., via the electric arc process or by using (clean) hydrogen e.g., for the direct reduction process, leading to lower emissions caused by the process. In essence, it is about achieving the same result through a different chemical reaction that releases less methane, carbon dioxide or other greenhouse gases. In the case of organic compounds, other factors play a role, too. In livestock farming, for example, adapting the feed can lead to better digestion and consequently lower methane emissions. In addition to chemical reactions, the production approach can also lead to emission savings. For instance, instead of lathes that remove material from the workpiece (and thereby potentially waste it), additive processes such as 3D printing and/or lightweight construction techniques can be used which fulfil the same requirements for the end product (e.g., stability) with a completely different approach and lower (energy and) material input.

Economic one-off effect: Significant *one-off investments* are required to avoid structurally induced process emissions through process adaptation (as all machines for this process have to be replaced at once). In addition to the investments themselves, there are also the production losses during the conversion and retooling process, i.e., lost margins and fixed costs nevertheless incurred. Therefore, such modifications make sense when major maintenance is due anyway, machines need to be replaced, or a new building is planned.

Lasting effect: Compared to the original process, the emissions released per output decrease, but the effect on energy- and other ongoing costs depends on the alternative production technique chosen. In fact, it can also happen that the energy input per product increases. Particularly but not exclusively in the chemical industry, it is important to weigh up carefully what effect a changeover will have on emissions and on energy requirements and costs, i.e., how much electricity and/or hydrogen is needed additionally, at what cost, with what embodied emission footprint, to avoid how many process- and energy-related emissions.
The boundary between an actual reduction in process emissions and the energy-related emissions from a process (e.g., from burning gas) is very thin. This applies in particular to process (and infrastructure) modifications that enable a switch to clean energy sources. An example of this is the electrically heated steam cracker furnace, which could enable the chemical industry to switch its most energy-intensive and complex process, which produces chemicals for many products, to another fuel (clean electricity) [23].

Conclusion: A change in process engineering and/or process technology *leads to a reduction of ongoing (process-related) emissions*. How this affects the *ongoing energy costs depends on the production technology chosen*. They can remain unaffected, decrease, but also increase.

Further reduction-related measure types:

Not discussed in detail, but also falling into this category, are *emission reductions* through a reduction of the scrap rate and a more efficient use of the material or the use of waste products, offcuts, or other leftovers. These material and resource efficiency measures also lead to ongoing cost savings, as less raw material is needed, or several/more things can be produced with the same amount of raw material. However, these savings in ongoing costs do *not necessarily* lead to *energy cost savings* (i.e., less off-cut does not lead to less energy used as the energy use per product output is not affected. Yet, less off-cut means less material and therefore less energy is needed to produce and transport the material. Depending on whether this material is produced on-site or by someone else off-site, these savings are either Scope 1/2 savings or Scope 3 savings, which are not considered in this report.

2.2 Substitution

“Substitution” includes those measures in which one energy source is replaced by another energy source of similar value. Value refers to both the “calorific value”, which can vary across fuels (i.e., for a litre of petrol depending on its octane figure and whether it is bio-based or fossil-based), and the effectiveness of the substitute in achieving the desired outcome (i.e., the quantities – and associated calorific values – needed to reach a certain temperature). Conversion losses can also play a role (e.g., converting clean electricity into hydrogen instead of directly using the electricity, or heat radiation that is not used).

Measure type 3: Substitution with self-generated renewable energies

There are many ways to self-generate (or recover) energy. The main forms are hydropower, wind power, geothermal energy, solar energy (for electricity or heat) and bioenergy (biogas/biomass) [24]. Forms of heat recovery, such as heat pumps or waste heat conversion, are on the borderline of energy efficiency measures.

Economic one-off effect: *One-off investments* are required to explore which type of energy generation is possible at the site, as well as for the *acquisition*, *construction & commissioning of the technology itself*. While some renewable energy sources guarantee a continuous energy supply (e.g., geothermal energy), this fluctuates for most other energy sources. If the generation coincides with the time of energy demand, everything is fine. However, in most applications, a suitable energy storage system (e.g., thermal, electrical, mechanical or chemical [25]) is required to ensure a continuous energy supply or the smoothing of peak loads, and - or alternatively - a flexible external energy supply to cover potential gaps. Instead of or in addition to the one-off investment in an energy storage system, it is also possible to check which energy consumption could be automatically throttled or switched off (or the energy source changed) without any problems during periods of insufficient generation. The Kopernikus Project “SynErgie” explores means to facilitate the development and implementation of energy adaptive production technologies and approaches in industry. It builds on nine different forms of energy demand flexibilisation, originally described by Grassl and Reinhart [26](p. 130), that can be considered, including virtual storage, but these are not discussed in further detail here [27].

Lasting effect: Although there are additional ongoing maintenance costs apart from biogas, and possible charges for the use/diversion/discharge of water, the ongoing costs for on-site energy generation are - in most cases - very low or even zero in relative terms.

Conclusion: The construction of an energy generation plant on one’s own premises requires in most cases an accompanying storage and/or flexibilisation approach and *reduces the ongoing energy-related emissions* and the *ongoing energy costs* (in most cases) to almost zero.

Measure type 4: Substitution through the purchase of renewable energies

Instead of generating renewable energies oneself, they can also be sourced from outside. This can be done, for example, via district heating networks, biomass/biogas plants and in the form of gases or electricity from sustainable energy sources (see above).

Economic one-off effect: In most cases, no one-off investments are required for the purchase of renewable energies. In some cases, connection fees may apply (e.g., for connection to a district heating network).

Lasting effect: The price for a kilowatt hour (kWh) of renewable energy in “green electricity tariffs” is currently often still higher than a kWh in a “standard tariff”, as energy providers often add a surcharge to the otherwise increasingly competitive price in order to finance the expansion of renewable generation facilities. Indeed, technological advances and other effects (e.g., social value, emission price schemes that make fossil generation more expensive) mean that energy generation from renewable sources is increasingly competitive or more competitive than conventional energy generation. Nonetheless, it will still take time before these competitive plants account for the largest share of renewable energy generation and thus are more competitive on average. Moreover, the geographical location has a large impact on the cost competitiveness (i.e., differing solar radiation, strength of wind, tidal range, geology)[28,29]. Therefore, the ongoing energy costs may even increase a bit in some cases.

Conclusion: The purchase of renewable energies, especially in electrical form, is easy, as it often only requires switching to an appropriate tariff. However, the *ongoing energy costs* (often) *increase* and availability is still more limited than conventional generation, which can also have an impact (i.e., excess demand can drive unit price or limit access to such a tariff). At the same time, the *ongoing energy-related emissions are reduced* to near zero (in most cases).

Further measure types to substitute fossil energy carriers:

Participation in (external) energy generation plants is a mixed form, which - apart from the location outside the own premises - differs from local self-generation mainly because the energy is first fed into the public energy grid, and expenses are incurred for this. More and more large and energy-intensive companies, such as BASF [30] or ArcelorMittal [31] are investing into "their own" wind farms to gradually be able to cover their energy needs from sustainable sources. However, in contrast to measure type 3, these are not located on their factory's premises. The (co-)ownership of the generation infrastructure leads to *one-off and maintenance costs*, but the *ongoing energy costs drop* to almost zero.
Another special form is power purchase agreements (PPAs). In contrast to energy tariffs, which are based on the price per unit, PPAs comprise a long-term contractual agreement on certain energy quantities for a fixed price. This provides security for both the energy supplier (secure revenue at a fixed price) and the customer (guaranteed access and usually no price risks). Unsurprisingly, according to the wind energy association WindEurope [32], corporate wind energy PPAs have become quite popular among large energy users, as also shown by the announcements of Covestro [33], or the cement company OPTERRA [34].
While in PPAs long-term agreements are made and the source of energy (i.e., the wind farm) is sometimes built just to serve one specific customer, there is *no co-ownership or direct investment* by the customer, so *ongoing energy costs continue*.
Both mixed forms result in *ongoing energy-related emissions approaching zero* and are not discussed in further detail here.

The substitution of materials can also reduce emissions, especially with regard to the product-related footprint. This is the case, for example, with the addition of recovered paper in paper production, of scrap metals in iron, steel and copper production, or recycled plastic in many products made of synthetic fibres and materials, such as clothing.

The substitution by less CO_2-containing energy sources (e.g., coal by gas), mentioned in other approaches in this context, is not addressed in this report. From the authors' point of view, this can only be a transitional solution.

2.3 Compensation

Compensation refers to those voluntary and involuntary measures that aim to offset the effects of energy- or process-related emissions, but do not prevent the emissions themselves.

Measure type 5: Compensation through certificates or projects

Two types of measures can be distinguished: firstly, the purchase of emission allowances. For example, if a state or a company emits less than the emission allowances allocated to it or purchased by it allow, it can sell on the surplus allowances. Manufacturers of electric vehicles, for example, have been able to generate considerable revenue with this in the past [35]. Secondly, climate protection projects can lead to emission reductions and get issued emission reduction certificates, which can be used to offset one's own surplus GHG emissions, through emission reductions somewhere else and not at one's own location.

Economic one-off effect: Although the purchase of certificates is made selectively or a project is financed on a one-off basis, it is not a one-off economic effect in the context of this publication, as it needs to be repeated continuously to offset emissions as they arise (i.e., if a company emits 100 tonnes of CO_2-eq. per year, then it needs to find projects to finance each year to offset the new 100 tonnes of emissions). However, one-off search costs may be incurred for the identification and due diligence of suitable projects. These costs take the form of staff hours or direct cost (i.e., for service providers, consultants or subscriptions to platforms) – both are 'transaction costs' that need to be taken into account in the overall financial assessment.

Lasting effect: Energy-related and process-related emissions continue to occur as a result of ongoing economic activity. Offsetting these emissions is therefore an ongoing additional expense.

Conclusion: The ongoing energy costs and the *emitted emissions* remain unchanged, but the emissions are *offset elsewhere*. This incurs additional ongoing costs, which could increase if the availability of suitable compensation options is scarce.

This only applies to measures where emissions reductions are certified for the entire lifetime and permanence is assumed without further ongoing costs (e.g., financing the planting of a tree). The other form of climate protection projects, where a one-off investment and ongoing costs are incurred in return for generating annual emission reduction certificates (e.g., building a wind farm), is not considered in this example. In contrast to the one-off example, such a multi-year project can offer predictability, initially high but in the long-run lower costs per tonne of offset emissions, and instead of search-costs for suitable projects there are maintenance, operating and certification costs.

Measure type 6: Compensation through storage, binding & use

Another form of compensation (which is not permitted everywhere, however [36]) is the capture and storage of emissions as they arise (carbon capture and storage, CCS) [37] or their further processing and use as raw material elsewhere (carbon capture and utilisation, CCU), for example in the chemical or building materials industry [38]. The amount of CO_2 permanently stored (CCS) or used (CCU) reduces the GHG emission balance of the company, and thus decreases the amount of GHG that needs to be addressed by measure types 1-5 (as achieving zero emissions is not feasible with CCS/CCU alone).

Economic one-off effect: So far, there are only a few installations. Considering the often still experimental nature of the facilities, significant one-off investments are to be expected and there is still little, but increasingly more, information on the predicted one-off- and ongoing costs [39]. Moreover, these largely depend on how and where the emissions are to be stored (i.e., on-site or in depleted oil wells), how much needs to be stored (as this contributes to operational expenditure (OPEX) and equipment limitations), the type of storage medium, and how the emissions are captured and transported there (i.e., pipeline or ship).

Lasting effect: Energy is needed to operate a CCS/CCU plant, which means that *additional ongoing energy costs* will be incurred. In the case of CCS, additional ongoing (transport and) storage costs might arise.

Conclusion: Current emissions are not avoided, but they are reduced and prevented from causing harm. If they are used in a converted form as a substitute elsewhere, they can reduce emissions there. The *ongoing energy costs* from the actual economic activity remain *unchanged*. Nevertheless, the factory may incur *additional ongoing energy/operating/transport/storage* costs for the CCS/CCU plant, which in the case of CCU can be partially offset by additional ongoing revenues. Typically, CCU/CCS is a solution for hard-to-abate sectors (i.e. chemical and petrochemical industries, iron and steel and cement)[40,41] and fossil energy generation (i.e., gas and coal-fired power plants)[42,43].

Further measure types to offset emissions:

In addition to the two types of measure types described, there is a separate category of approaches: Carbon Dioxide Removal (CDR) or Negative Emission Technologies (NETs). In contrast to approaches that avoid or reduce *fossil* GHG emissions, carbon-negative approaches actively remove emissions from the atmosphere, which means that they permanently store *atmospheric* or *biogenic* carbon dioxide. The International Energy Agency distinguishes between nature-based solutions (e.g., afforestation, reforestation), enhanced natural processes (e.g., storing emissions in the soil, enhanced weathering, or ocean fertilisation) and technological solutions (e.g., bioenergy with carbon capture and storage (BECCS) or direct air capture and carbon storage (DACCS))[44].

All these solutions have the potential to remove emissions but come with *additional one-off and often also energy- and other ongoing costs*, e.g., for maintenance or general transaction costs.

2.4 Reference Scenario: Do not act

Although non-action means that "neutrality" in any form (carbon-, climate-, environmental-) is not a goal, it is necessary to mention it in terms of opportunity costs – i.e., the costs of the action alternative/non-action.

Economic one-off effect: There are no investments.

Lasting effect: In countries and regions where there is an emissions price on energy- and/or process-related emissions, the ongoing costs will increase by the amount of the current emissions multiplied by the price of the respective emission type. This is not the case in countries and regions *without* emission charges on energy- and/or process-related emissions. However, if a company manufactures in a country/region without emission levies, but carbon border adjustments (CBAM) are in place in the country/region to which the company wants to export its products, the situation changes [45,46]. An emissions levy *may* be charged per exported product unit, which is based on the product carbon footprint (PCF) and aligned with the emissions price of the target market [47]. Such additional ongoing costs may also be incurred – regardless of whether emission prices or CBAMs are in place- if customers insist on the delivery of products with a reduced or net-zero product PCF [48].
The nature/extent of the immediate economic effects of inaction – apart from progressive climate change and its effect on the general and immediate local weather, ecosystem, etc. – mainly depends on where the emitter is located geographically, and what rules apply there.

Conclusion: Although *neither emissions nor ongoing energy costs are reduced*, depending on the location, noticeable *additional ongoing costs can be incurred* for the emissions released. Depending on the pricing model, these costs per unit of emissions can vary. If these revenues flow to state actors and are used for climate protection projects, at least a part of the emissions is offset – but not in countries and regions without an emissions price. There, external incentives for decarbonisation arise at best through calls for action by the public/customers, investors, supply chains, or as a result of other (regulatory) measures.

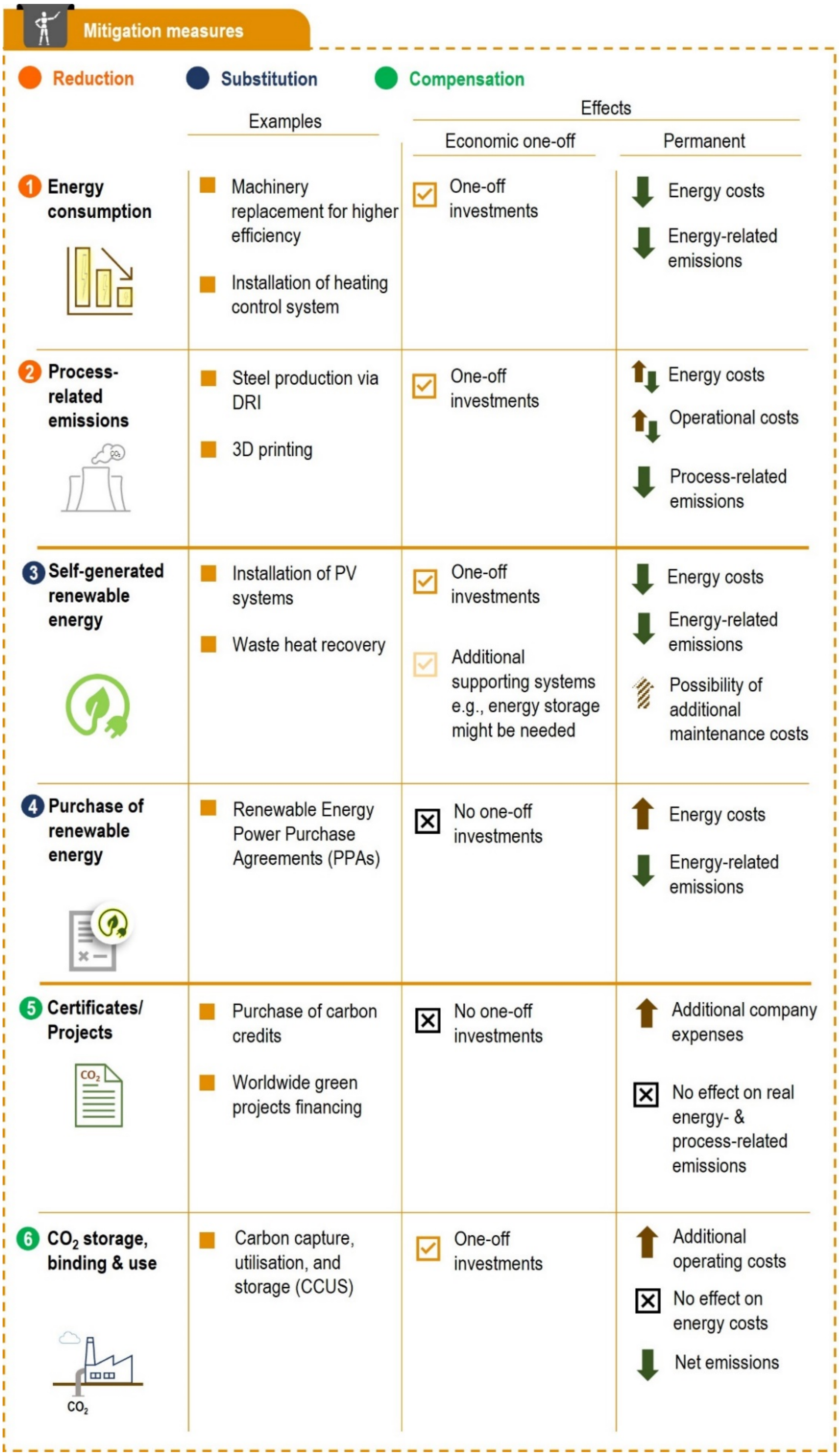

Figure 3. Overview of the six types of measures and their impact

Knowing the economic impacts of the described six types of measures in terms of one-off and ongoing costs, as well as knowing one's own emissions, can already help in the selection and prioritisation of possible measures to achieve net-zero emissions (cf. **Figure 3**). However, in order to determine an economic mix of measures, it is essential to also take into account higher-level interrelationships and external influencing factors.

3. System view: external factors with strong influence

After the general economic analysis of the types of measures, the latter have to be assessed in the context of one's own objectives and the overall system in which one operates in: taking into account, on the one hand, legal and regulatory requirements, geographical circumstances, and the availability on the market and, on the other hand, societal expectations and the impact of one's own choice of (non-)action.

With regard to an "easy" and "quick" implementation, the purchase of renewable energies (measure type 4) or the investment in emission reduction certificates, as well as in climate protection projects brokered by third parties (type 5) appear to be the obvious solution.

However, if one considers (for example) the share of renewable energies in total electricity generation in 2019 (see **Table 1**; i.e., World: 26 %, EU-27: 34 %, industrial economy, e.g., Germany: 40 %) and puts this in the context of the electricity demand of by industry (42 %, 36 %, 45 %), it becomes clear that a widespread decision for a "simple" change of the electricity tariff will lead to excess demand almost everywhere (cf. light red in **Table 1)** [49-51]. The latter particularly constitutes an ongoing issue in geographies where the expansion of renewable generation and transmission infrastructure is progressing more slowly slower than the demand for it. There is no notable change if other forms of low carbon generation (i.e., nuclear) are added, except in the case of OECD countries, as illustrated in **Table 1**: where renewable or low carbon supply (= renewables + i.e., nuclear) exceeds industry demand, the cell is highlighted green; where it is at the same level, yellow; where it is less than the industrial sector's final demand, red.

Table 1. Share of renewable generation compared to share total electricity consumed by industry; own computation based on data from IEA World Energy Balances Highlights [49] and Eurostat [50,51].

2019	Electricity (Totals)			Energy (Totals)		
Regions [49] \ Shares	Supply		Final Consumption	Supply		Final Consumption
	renewables	low carbon	Industry	renewables	low carbon	Industry
World	26%	36%	42%	14%	19%	29%
OECD	27%	45%	32%	12%	21%	22%
Non-OECD Total	25%	30%	49%	16%	19%	35%
Non-OECD Americas	68%	70%	38%	34%	36%	28%
Non-OECD Europe and Eurasia	19%	37%	42%	5%	12%	27%
Non-OECD Asia (incl. China)	25%	29%	55%	14%	16%	43%
Middle East	3%	3%	23%	1%	1%	28%
Africa	21%	22%	38%	48%	48%	14%
EU-27 [50,51]	34%	.	36%	20%	.	26%
China	27%	32%	60%	10%	12%	49%
Germany	40%	52%	45%	16%	22%	25%
Italy	40%	40%	41%	19%	19%	21%
Japan	18%	24%	36%	8%	12%	29%
South Africa	5%	10%	52%	6%	8%	38%
USA	18%	37%	20%	8%	18%	17%

Even without sector coupling, e-mobility and process decarbonisation, this (excess) demand cannot be met at present and could lead to price increases for green electricity tariffs. Moreover, in the context of the energy system, this would amount to a zero-sum game in terms of emissions, as the footprint of the standard electricity mix deteriorates to the same extent as it improves for tariff switchers (and as the overall electricity mix remains unchanged without capacity expansions). Climate risks (e.g., droughts), but also other severe events (e.g., earthquakes, wars, structural failures) can lead to reduced electricity supply as power stations cannot generate (e.g., lack of cooling for thermal and nuclear power plants) or distribute energy (if transmission lines or distribution nodes are impaired). This dynamic drives up the unit price for energy (unless self-generated or delivered in context of a PPA), especially in "merit order" driven electricity markets, where the "most expensive" source of energy determines the spot market price for all electricity sold. Climate risks and other events can also affect on-site generation, but the risk is lower, and reducing energy and resource demand in the first place promotes energy resilience to such availability and price shocks.

As already indicated, electricity is not the only form of energy that the industrial sector needs for its operations. Switching all energy needs (including oil, gas, coal, etc.) to renewable or low-carbon sources might be more difficult than switching from the standard electricity mix to low-carbon electricity. This is because (a) the gap to meet the industrial sector's needs is larger in most places (cf. **Table 1**) and (b) many of the alternatives are less mobile or require new infrastructure, unlike renewable electricity that is already connected to the grid.

Since the *availability of emission reduction certificates* and *credible climate protection projects* (and those who can identify, check, plan and implement them) is also limited, these effects of excess demand are not only connected to a shortage of renewable energies on the market. In addition, there is an increased risk of falling prey to dishonest projects that ultimately damage the company's image and have no protective effect on the climate (e.g., reforestation on an area that is explicitly cleared for this purpose or reforestation that is cleared again a few years later or protecting a forest that is not endangered)[52-55]. Therefore, it is important to look out for Certified Emission Reductions (CERs) that are in line with the Sustainable Development Mechanism (SDM). The latter succeeds the Clean Development Mechanism (CDM) introduced with the Kyoto Protocol, and follows the rules set out by Article 6 of the Paris Agreement, ensuring “permanence”, “additionality” and ruling out “double-counting” [56,57]. As a consequence, there can be no legitimate CERs generated from projects located within the European Union, for example, as emission reduction projects in the region are counted directly against the EU emissions inventory; projects carried out there may be undertaken “voluntarily” but cannot be counted against one's own emissions inventory (for reasons of double counting / additionality)[58].

Furthermore, regarding the expansion of transmission infrastructure and renewable energy generation, it is significant to notice that there is already a shortage of skilled workers in the construction sector and thematically relevant trades in many geographies [59,60]. This shortage is problematic since the increasing number of net-zero declarations by countries and companies is expected to lead to an increase in commissions of on-site decarbonisation measures, renewable generation & transmission infrastructure, and projects relating to climate protection. Given the limited capacity of local authorities, whose approval is oftentimes required, longer *waiting times* and possibly higher costs for priority treatment should be expected as well.

The bottom line is that it makes sense to prioritise on-site actions (measure types 1, 2, 3, 6) and to act quickly for several reasons: firstly, to build resilience against availability/price shocks, secondly, to reduce the risk of having to wait in line, and, thirdly, to minimise the “procrastination costs” of missed cost saving opportunities.

4. Consideration of price fluctuations

The one-off economic effects and ongoing impacts of the different types of decarbonisation measures are complemented by the effects of energy and emission price developments, as these influence how cost savings change over time. The investment costs at the time of planning are known from quotations. Although the ongoing costs change over time, the change is often analogous to a regular price increase and can thus be easily estimated. In contrast, energy prices often fluctuate more strongly and frequently [61], e.g., due to political developments. Looking at the price development of the European Union Emissions Trading Scheme (EU ETS)[62](cf. **Figure 4**), a significant increase can be observed after the announcement of tightened EU climate targets for 2030 (from -40 % to -55 % compared to 1990) on 11 December 2020 [63].

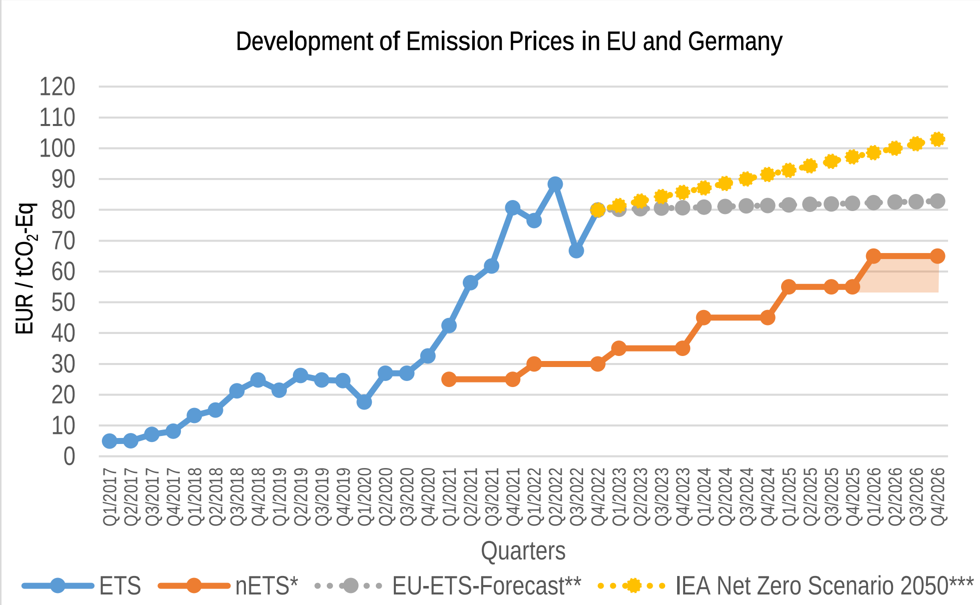

Figure 4. Exemplary emission price development: Market based system (EU ETS) and its forecasts for 2030 [17,62,64-66][3], as well as fixed-price system with staggered increases (German nETS)[67] that is charged on energy-related emissions not covered by EU ETS [68].

Various factors influence emissions and energy prices, but they can also influence each other. For instance, higher emission prices may lead to a rising demand for electricity from renewables and thereby increasing prices for green electricity (see **section 3**), unless the global expansion of renewable energies progresses in parallel to/in tandem with the rise in demand, effectively counteracting a price increase by augmenting supply.

Therefore, in the following deliberations, five of the six types of measures are considered with regard to the expected price fluctuations. The reference scenario, in which a company does nothing and is fully exposed to fluctuations, serves as a basis for comparison: If energy or emission prices rise, this leads to higher energy and emission costs.

Reduction measures (section 2.1) lead to:

- A permanent reduction in energy consumption/costs compared to the Reference Scenario (provided that energy is purchased externally, and it is a measure of the energy consumption reduction category (measure type 1)) and thus to *less dependence on the development of energy price developments, as they consume less.*
- A permanent reduction in emission(costs) compared to the Reference Scenario (regardless of which energy source is ultimately used and whether it is a reduction in energy consumption (1) or emissions (2)) and consequently to *less dependence on emission price developments, as they emit less*.

Substitution measures (section 2.2) lead to:

- A significant reduction in emissions as, for instance, the emission costs are lower in comparison with the reference scenario. In case of 100 % substitution with renewables (regardless of whether (3) or (4) is used) there is complete *independence from the emission price development* as no direct energy-related emissions arise.
- *A complete independence from energy prices developments* in the case of 100 % substitution through self-generation (3) in combination with buffer storage, as no direct energy costs are incurred.
- A *permanent dependence on the development of energy prices* and/or the *availability* of renewable energies when it comes to substitution through the purchase of renewable energies (4). The cold snap in Texas in February 2021 shows how quickly the

[3] * National Emissions Trading Scheme [67], ** first EU forecast for ETS price in 2030 due to "Fitfor55" at 85 EUR [65,66], *** required CO_2 price in IEA Net Zero 2050 Scenario for 2030 at 140 USD (2021 avg. ~ 120 EUR) [64]

availability of renewables, but also conventional energy generation, can dwindle and what massive consequences the failure of equipment can have [69,70]. The tariff and pricing of the supplier determine whether there are delivery guarantees or delivery failures, or whether a fixed price per kWh or the current spot price has been agreed – in other words, who bears the risk.

Measures to compensate through emission reduction certificates and climate protection projects (5, section 2.3) lead to:

- *No change in emissions* in case of offsetting 100 %, i.e., the amount of emissions is unchanged compared to the reference scenario. The emission costs are lower than the Reference Scenario, as the "penalty costs" (referring to emission prices) are higher compared to the certificate or project costs.
- *No change in energy consumption* in case of offsetting 100 %, i.e., the energy costs remain unchanged compared to the Reference Scenario.
- A complete *dependence on the certificate/project price development* if 100 % offsetting is sought through certificates or project financing (5). With steadily rising emission prices, this can, for example, result in many companies relying on offsetting via certificates or project financing (5), thus driving up the demand for certificates or projects and consequently the price for them. This price increase can be significant if there is a similar political reaction as after the Fukushima reactor disaster or if climate neutrality is targeted faster than before, both politically and socially. This case has been illustrated by the increase in EU ETS since the EU's decision to go climate neutral (cf. **Figure 4**).

However, the opportunity costs described so far and in particular the energy and emission price fluctuations are hardly systematically taken into account in the calculation of economic efficiency or economic consideration of alternative courses of action. Therefore, a new procedure is needed that ensures both the consideration of opportunity costs and the temporal component.

5. Recommendation for action

5.1 A new economic efficiency calculation

Up to now, the payback time has typically been used as a central decision criterion in economic efficiency calculations. Especially the simplified calculation of the *(static) payback time* is common practice, although this does not sufficiently reflect the actual economic efficiency of the measure [71].

Only in a few cases is the return, for example the *return on investment* (RoI) or the *internal rate of return* (IRR), calculated considering the period of use (useful life). Therefore, the useful life and the development of energy prices, which have often been disregarded, should be taken into account in the new economic efficiency calculation. Moreover, emission prices, which are or have been introduced in many geographies in the meantime, should also be taken into account. Therefore, for this new economic efficiency calculation, it is proposed to use the following formula for each measure option to calculate the savings:

Equation 1. Calculation of aggregated savings for a measure option

$$\begin{aligned} Savings\ (N,E) = {} & \sum_{t=1}^{N}\sum_{e=1}^{E}\Big(Energy\ price_{Reference}(t,e) * Energy\ amount_{Reference}(t,e) \\ & - Energy\ price_{New}(t,e) * Energy\ amount_{New}(t,e)\Big) \\ & + \sum_{t=1}^{N}\sum_{e=1}^{E}\Big(Emission\ price_{Reference}(t,e) * Emission\ amount_{Reference}(t,e) \\ & - Emission\ price_{New}(t,e) * Emission\ amount_{New}(t,e)\Big) \end{aligned}$$

The calculation is based on the intended period of use (**N**) of the measure option (e.g., time **t** in years) during which the savings are accrued and on all energy sources (**E**) used (e.g. $\mathbf{e_1}$ = electricity, $\mathbf{e_2}$ = gas, etc.). The formula calculates the difference in energy and emission-related costs between the reference scenario (described in **section 2.4**) and the outcome of implementing one of the measure options (a scenario). The continuous change in energy and emission prices is also considered.

For this reason, there are two groups of variables. Variables with the suffix "Reference" refer to the scenario in which no action is taken (at any time):

- **Energy amount** $_{\textbf{Reference}}$ is the energy consumed for each energy source; since no measure is taken, the energy quantities for each energy source remain constant over time.
- **Emission amount** $_{\textbf{Reference}}$ is the sum of the energy-related emissions caused by the consumption of the **Energy amount** $_{\textbf{Reference}}$ per energy source and the process-related emissions; since no measure is taken, it also remains constant over time.
- **Energy Price** $_{\textbf{Reference}}$ is the price per unit that applies for each energy source; depending on the **Energy amount** $_{\textbf{Reference}}$ the price per unit might be different (a different price level may apply depending on the amount used); it is not constant and changes over time.
- **Emission Price** $_{\textbf{Reference}}$ is the price per unit of emissions that must be paid as an emission charge on the **Emission amount** $_{\textbf{Reference}}$; it can change over time.

  Depending on the region/country and energy source, the emissions price may already be included in the energy price (e.g. for electricity in the EU, as electricity producers are covered by the EU ETS and pass on the cost of this in the electricity price). This is not the case for the examples in the following sections.

Variables with the suffix "New" reflect the measure option considered:

- **Energy amount** $_{\textbf{New}}$ can be lower than the **Energy amount** $_{\textbf{Reference}}$ (measure type 1) and the energy sources can be different (3, 4);
- **Emission amount** $_{\textbf{New}}$ can be lower than the **Emission amount** $_{\textbf{Reference}}$ (1, 2, 3, 4);
- **Energy Price** $_{\textbf{New}}$ differs from the **Energy Price** $_{\textbf{Reference}}$ in case of a change of energy sources (3, 4) or a decrease in energy consumption (1) which leads to the application of a different price level;
- **Emission Price** $_{\textbf{New}}$ differs from the **Emission Price** $_{\textbf{Reference}}$ as it is the price for emission reduction certificates and projects (5) or the price to capture and store emissions (6).

The variables with the suffix "Reference" and "New" are primarily intended for the calculation of savings compared to the initial state. In this context, "New" is not always identical with the (total) remaining amount of energy or emissions after implementation of a measure.

This can occur in the following cases:

- if only a part of the emissions or energy consumption is addressable/addressed by the measure and the old price (Reference) is applied for the "remaining ones".
- if the emissions are addressed but still exist (CCUS, (6)).

As a result, for example, the **Emission amount** $_{\textbf{New}}$ in the calculation of measure types 4 and 6 is lower than the **Emission amount** $_{\textbf{Reference}}$. For measure type 4, this is consistent with the facts: renewable energies cause fewer emissions. For measure type 6, on the other hand, the emission quantities remain the same in reality, since storage does not change the existence of the emissions themselves.

The following procedure is suggested for applying the formula:

1) Map the current situation by determining
   a) the energy consumption and energy costs separated by energy sources,

b) the emissions of the consumed energy (using the emission factors of each energy source), converted in CO_2-equivalents, and the corresponding emission costs,

c) the process-related emissions, converted in CO_2-equivalents, and the associated emission costs (if applicable)

to obtain all reference variables.

2) Make assumptions about

a) the future development of energy prices, which can be made on the basis of scenarios of the International Energy Agency (IEA), such as the Stated Policies Scenario (STEPS) [72],

b) the future development of emission costs, whereby staggered fixed prices for emission allowances (such as in the nETS under the German Fuel Emission Trading Act BEHG until 2025 [16]) or forecasts of emission price developments can be used,

c) the impact of the measure option on, for example, the amount of energy, energy-related emissions, or process-related emissions

to obtain all new variables.

3) Calculate the aggregate savings (**N, E**) until year **(t_x)** with the above-mentioned formula (cf. **Equation 1**).

5.2 Guiding remarks for applying the new economic efficiency calculation

In order to realistically depict the effect of energy and emission price developments in the following examples, one can either (a) use scenarios (e.g. from the IEA [72]), or (b) use actual data from the recent past. If it is only a matter of practising the application of the formula, (c) a simple linear development or (d) constant prices can be assumed for the calculation.
If there is no price on emissions in the region of the intended application, one can set the value for this to 0 in the formula and can still see what price effect any voluntary measures or measures demanded by the customers/destination country have.

Similarly, performance data of projects that have already been carried out can be used to obtain a realistic estimate for investment costs, ongoing costs (maintenance, etc.) and the associated changes in emissions and energy consumption. Whether these projects have been carried out by the company itself, originate from an offer, or represent the best-practice example of a third party is irrelevant for the example calculation.
As the many measures within the described categories of measure can be quite different and the assumption of “any” figures could give a wrong impression about the financial performance of the measure, we only address the savings in the examples, but not the required investments and related costs.
Moreover, this aspect is used in many calculation approaches and should therefore be sufficiently familiar.

For more complex scenarios with multiple energy sources, differing energy- and emission prices the formula(s) (cf. **Equation 1**, etc.**)** needs to be applied accordingly. This includes, but is not limited to, different unit prices depending on the type of energy chosen (i.e., taking into account the frequent mark-up for renewable energy tariffs), different costs per tonne of emissions for emission prices, emission reduction certificates and climate protection projects (including the associated transaction costs). In the examples provided, this is also the case when less than 100 % of the energy or emissions are addressed by one measure: in such case, the “old” energy price or emission price (Reference price) is applied to the amount of energy or emissions not addressed by the sample measure. The share addressed by the measure is charged the “new” energy or emission price.

5.3 Applying the new economic efficiency calculation: examples for the six measure types

To illustrate the calculation, examples of different measures with exemplary figures are provided in this sub-section. A number of simplifying assumptions are made to ease the application. Then the calculation is carried out for the Reference Scenario and the six types of measures.

Assumptions:

To highlight the differences between measures, the examples of the new economic efficiency calculation are kept simple and contain fixed assumptions to make the economic effects more visible:

1) One energy source: electricity with an emission factor of 0.4 gCO_2-eq/kWh
2) Energy price: 20 ct[4]/kWh with a linear increase of 2 % per year
3) Emission price: 30 EUR/tCO_2-eq with an increase of 5.00 EUR per tCO_2-eq per year

In all example calculations, it is assumed that a company, in the base year (**t** = 0 = $\mathbf{t}_{0}$) has a total energy consumption of **1,000 MWh** (electricity only) and annual emissions of **600 tCO_2-eq** (400 tCO_2-eq *energy-related* and 200 tCO_2-eq *process-related*). It is further assumed that in the base year the company sets the target to achieve net-zero emissions within 30 years (t = 30 = $\mathbf{t}_{\text{net-zero}}$). To work towards this goal, it successfully implements a measure option during t_0. The full effect of the implemented measure option is visible starting from the first full year (t = 1 = $\mathbf{t}_{1}$). To show the effect of the measure over time, the values of the individual variables are calculated for the first five years, the first milestone after 10 years (t = 10 = $\mathbf{t}_{\text{milestone}}$) and the target year ($\mathbf{t}_{\text{net-zero}}$).

Additional assumptions are made for the calculation of the exemplary scenarios (cf. scenario description).

To improve the visibility of the effect of implemented measures, the variables with the suffix “New” are not shown in the tables if they have the same value as the variables with the suffix “Reference”.

Reference Scenario: No action is taken

In the reference scenario, the company (located in an area where emission charges are levied) decides not to set an emission savings target and not to act. Therefore, **energy consumption** and the **annual emission amounts** remain the same over the years, whereas the total (ongoing) costs (= energy costs + emission costs) increase every year due to rising prices (see assumptions). **Table 2** displays the cost development over time, from $\mathbf{t}_{0}$ to $\mathbf{t}_{\text{net-zero}}$.

Table 2. Exemplary reference scenario with assumed amounts and prices for energy and emissions.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount Reference	Emission price Reference	Emission costs Reference	Total Costs Reference
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000
t_1	1.000	20.40	204,000	600	35.00	21,000	225,000
t_2	1.000	20.81	208,080	600	40.00	24,000	232,080
t_3	1.000	21.22	212,242	600	45.00	27,000	239,242
t_4	1.000	21.65	216,486	600	50.00	30,000	246,486
t_5	1.000	22.08	220,816	600	55.00	33,000	253,816
(...)							
t_{10}	1.000	24.38	243,799	600	80.00	48,000	291,799
(...)							

[4] Ct = Eurocent, 10 Ct = 0,10 EUR

t_{30}	1.000	36.23	362,272	600	180.00	108,000	470,272

Measure type 1: Energy efficiency

In this scenario, the company takes action and implements one measure of type 1 (energy efficiency) in **t_0**, which leads to a decrease in energy consumption in **t_1** (700 MWh instead of 1000 MWh, cf. dark green in **Table 3**) and to less energy-related emissions (280 tCO_2-eq instead of 400 tCO_2-eq, cf. light green in **Table 3**). As a result, the ongoing energy and emission costs decrease, leading to savings in total (ongoing) costs compared to the reference scenario. The column **Savings (N,°E,°t)** lists the savings (**Total Costs $_{Reference}$ (t) – Total Costs $_{New}$ (t)**) for the respective year **t_X**.

Table 3. Exemplary scenario in which a measure of type 1 (energy efficiency) is implemented.

	Energy amount New	Energy price Reference	Energy costs New	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	700	20.40	142,800	480	35.00	16,800	159,600	65,400
t_2	700	20.81	145,656	480	40.00	19,200	164,856	67,224
t_3	700	21.22	148,569	480	45.00	21,600	170,169	69,072
t_4	700	21.65	151,541	480	50.00	24,000	175,541	70,946
t_5	700	22.08	154,571	480	55.00	26,400	180,971	72,845
(...)								
t_{10}	700	24.38	170,659	480	80.00	38,400	209,059	82,740
(...)								
t_{30}	700	36.23	253,591	480	180.00	86,400	339,991	130,282

Measure type 2: process decarbonisation

In this scenario, the company implements one measure of type 2 (process decarbonisation) in **t_0**, which leads to a decrease in process-related emissions in **t_1** (150 tCO_2-eq instead of 200 tCO_2-eq, cf. dark green in **Table 4**). This reduces the ongoing emission costs and consequently the total (ongoing) costs compared to the reference scenario. The column **Savings (N,°E,°t)** lists the savings (**Total Costs $_{Reference}$ (t) – Total Costs $_{New}$ (t)**) for the respective year **t_X**.

Table 4. Exemplary scenario in which a measure of type 2 (process decarbonisation) is implemented.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1,000	20.40	204,000	550	35.00	19,250	223,250	1,750
t_2	1,000	20.81	208,080	550	40.00	22,000	230,080	2,000
t_3	1,000	21.22	212,242	550	45.00	24,750	236,992	2,250
t_4	1,000	21.65	216,486	550	50.00	27,500	243,986	2,500
t_5	1,000	22.08	220,816	550	55.00	30,250	251,066	2,750
(...)								
t_{10}	1,000	24.38	243,799	550	80.00	44,000	287,799	4,000
(...)								
t_{30}	1,000	36.23	362,272	550	180.00	99,000	461,272	9,000

Measure type 3: self-generation of renewable energy

In this scenario, the company implements one measure of type 3 (self-generation of renewable energy) in **t** $_0$. Half of the annual energy demand can be self-generated, which means 500 MWh out of 1,000 MWh (cf. dark green in **Table 5**). Only 500 MWh still have to be purchased externally. This leads to a decrease in energy costs and the energy-related emissions in **t** $_1$ (cf. dark green in **Table 5**) compared to the reference scenario. The column **Savings (N,°E,°t)** shows the savings (**Total Costs** $_{Reference}$ **(t)** – **Total Costs** $_{New}$ **(t)**) for the respective year **t** x.

Table 5. Exemplary scenario in which a measure of type 3 (self-generation of renewable energy) is implemented.

	Energy amount New	Energy price Reference	Energy costs New	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	500	20.40	102,000	400	35.00	14,000	116,000	109,000
t_2	500	20.81	104,040	400	40.00	16,000	120,040	112,040
t_3	500	21.22	106,120	400	45.00	18,000	124,121	115,121
t_4	500	21.65	108,243	400	50.00	20,000	128,243	118,243
t_5	500	22.08	110,408	400	55.00	22,000	132,408	121,408
(...)								
t_{10}	500	24.38	121,899	400	80.00	32,000	153,899	137,899
(...)								
t_{30}	500	36.23	181,136	400	180.00	72,000	253,136	217,136

Measure type 4: purchase of renewable energy

In this scenario, the company implements one measure of type 4 (purchase of renewable energy) in **t** $_0$. All the energy consumed originates from renewable sources. This means the energy-related emissions drop to zero. Only the process-related emissions remain (200 MWh, cf. dark green in **Table 6**), leading to a decrease in emission costs in **t** $_1$ compared to the reference scenario. The column **Savings (N,°E,°t)** lists the savings (**Total Costs** $_{Reference}$ **(t)** – **Total Costs** $_{New}$ **(t)**) for the respective year **t** x.

Table 6. Exemplary scenario in which a measure of type 4 (purchase of renewable energy) is implemented.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1,000	20.40	204,000	200	35.00	7,000	211,000	14,000
t_2	1,000	20.81	208,080	200	40.00	8,000	216,080	16,000
t_3	1,000	21.22	212,242	200	45.00	9,000	221,242	18,000
t_4	1,000	21.65	216,486	200	50.00	10,000	226,486	20,000
t_5	1,000	22.08	220,816	200	55.00	11,000	231,816	22,000
(...)								
t_{10}	1,000	24.38	243,799	200	80.00	16,000	259,799	32,000
(...)								
t_{30}	1,000	36.23	362,272	200	180.00	36,000	398,272	72,000

Measure type 5: compensation through certificates or projects

In this scenario, the company implements one measure of type 5 (compensation through certificates or projects) in **t** $_0$. All (energy-related and process-related) emissions are offset by certificates, whereby the costs for certificates are 40% lower than for emission allowances (cf. dark green in **Table 7**). This leads to a decrease in the emission costs in **t** $_1$ compared to the reference scenario. The column **Savings (N, E, t)** shows the savings (**Total Costs** $_{\text{Reference}}$ **(t) – Total Costs** $_{\text{New}}$ **(t)**) for the respective year **t** $_X$.

Table 7. Exemplary scenario in which a measure of type 5 (compensation through certificates or projects) is implemented.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount Reference	Emission price New	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1,000	20.40	204,000	600	21.00	12,600	216,600	8,400
t_2	1,000	20.81	208,080	600	24.00	14,400	222,480	9,600
t_3	1,000	21.22	212,242	600	27.00	16,200	228,442	10,800
t_4	1,000	21.65	216,486	600	30.00	18,000	234,486	12,000
t_5	1,000	22.08	220,816	600	33.00	19,800	240,616	13,200
(...)								
t_{10}	1,000	24.38	243,799	600	48.00	28,800	272,599	19,200
(...)								
t_{30}	1,000	36.23	362,272	600	108.00	64,800	427,072	43,200

Measure type 6: carbon capture, storage, binding and use

In this scenario, the company implements one measure of type 6 (carbon capture, storage, binding and use) in **t** $_0$. Almost all process-related emissions are captured and stored with CCS technology, so that emission costs are only incurred for energy-related emissions (400 of the 600 tCO_2-eq, cf. dark green in **Table 8**). This leads to a decrease in emission costs in **t** $_1$ compared to the reference scenario. The column **Savings (N, E, t)** shows the savings (**Total Costs** $_{\text{Reference}}$ **(t) – Total Costs** $_{\text{New}}$ **(t)**) for the respective year **t** $_X$.

Table 8. Exemplary scenario in which a measure of type 6 (carbon capture, storage, binding and use) is implemented.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1,000	20.40	204,000	400	35.00	14,000	218,000	7,000
t_2	1,000	20.81	208,080	400	40.00	16,000	224,080	8,000
t_3	1,000	21.22	212,242	400	45.00	18,000	230,242	9,000
t_4	1,000	21.65	216,486	400	50.00	20,000	236,486	10,000
t_5	1,000	22.08	220,816	400	55.00	22,000	242,816	11,000
(...)								
t_{10}	1,000	24.38	243,799	400	80.00	32,000	275,799	16,000
(...)								
t_{30}	1,000	36.23	362,272	400	180.00	72,000	434,272	36,000

5.4 Economic effects of the sequence of implementation of measure types

The calculations of the exemplary scenarios for the six types of measure types show the different economic effects of each measure type. However, the sequence of implementation is also important.

To illustrate the differences, the calculation for two measure types (energy efficiency (1) and purchase of renewable energy (4)) is shown below in different orders.

Scenario 1: first measure type 1, second measure type 4

In this first scenario, the company takes action and implements a measure of type 1 (energy efficiency) in $\mathbf{t_0}$, which leads to a decrease in energy consumption in $\mathbf{t_1}$ (700 MWh instead of 1000 MWh, cf. dark blue in **Table 9**) and fewer emissions (480 tCO_2-eq instead of 600 tCO_2-eq, cf. light blue). One year later, in $\mathbf{t_1}$, another measure (type 4 – purchase of renewable energy) is implemented, which leads to fewer emissions in $\mathbf{t_2}$ (200 tCO_2-eq instead of 480 tCO_2-eq, cf. orange).

Table 9. Exemplary scenario in which first a measure of type 1 and then a measure of type 4 is implemented.

	Energy amount New	Energy price Reference	Energy costs New	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	700	20.40	142,800	480	35.00	16,800	159,600	65,400
t_2	700	20.81	145,656	200	40.00	8,000	153,656	78,424
t_3	700	21.22	148,569	200	45.00	9,000	157,569	81,672
t_4	700	21.65	151,541	200	50.00	10,000	161,541	84,946
t_5	700	22.08	154,571	200	55.00	11,000	165,571	88,245
(...)								
t_{10}	700	24.38	170,659	200	80.00	16,000	186,659	105,140
(...)								
t_{30}	700	36.23	253,591	200	180.00	36,000	289,591	180,682

Scenario 2: first measure type 4, second measure type 1:

In this second scenario, the order of measures is reversed compared to scenario 1 to show the effects of prioritising measures (cf. **Table 10**).

Table 10. Exemplary scenario in which first a measure of type 4 and then a measure of type 1 is implemented.

	Energy amount New	Energy price Reference	Energy costs New	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1.000	20.40	204,000	320	35.00	11,200	215,200	9,800
t_2	700	20.81	145,656	200	40.00	8,000	153,656	78,424
t_3	700	21.22	148,569	200	45.00	9,000	157,569	81,672
t_4	700	21.65	151,541	200	50.00	10,000	161,541	84,946
t_5	700	22.08	154,571	200	55.00	11,000	165,571	88,245
(...)								
t_{10}	700	24.38	170,659	200	80.00	16,000	186,659	105,140
(...)								
t_{30}	700	36.23	253,591	200	180.00	36,000	289,591	180,682

When looking at the savings it is obvious that the scenario 1 leads to higher savings in total. The reason for this is that measure type 1 has an effect on the amount of energy consumed and on the amount of emissions, making it is economically very attractive as it reduces both energy costs and emission costs. The decision to implement measure type 1 first leads to a savings advantage. Once both measures are implemented, the annual savings are equal.

5.5 Economic effects for different implementation scenarios

As described in **section 3**, it can be most attractive in terms of effort to change the energy tariff and to purchase renewable energy, as well as to compensate for remaining emissions (mainly process-related emissions).

Above all, taking measures on one's own property (energy efficiency, process decarbonisation and/or CCUS and self-generation of renewable energy) largely decouples one's business from external risks and shocks and thus increases resilience. Nevertheless, even then a certain amount of emissions and energy may remain that cannot be addressed locally (e.g. due to lack of space, technical inability to switch fuels or unavoidable process emissions).

"Self-sufficiency" makes little sense in most cases and usually requires further investment in various types of energy storage and forms of local generation, as well as in technologies that capture all remaining energy and process-related emissions.

Within the following scenarios, the general principle of reducing consumption first, substituting the remaining energy and material needs second, and then offsetting all remaining emissions is applied.

Scenario 3: On-Site (first measure type 1, second measure type 2, third measure type 3)

In this scenario, the company takes three on-site actions in sequential order. First, it implements a type 1 measure (energy efficiency) in **t_0**, which leads to a decrease in energy consumption (700 MWh instead of 1000 MWh, cf. dark blue in **Table 11**) and fewer emissions (480 tCO_2-eq instead of 600 tCO_2-eq, cf. light blue) in **t_1**. One year later, in **t_1**, another measure (type 2 – process decarbonisation) is implemented (430 tCO_2-eq instead of 480 tCO_2-eq, cf. orange). Then, a third measure (type 3 – self-generation of renewable energy) is implemented, resulting in less externally sourced energy consumption and fewer emissions in **t_3** (200 MWh instead of 700 MWh and 200 tCO_2-eq instead of 480 tCO_2-eq, cf. purple).

The remaining emissions could be reduced even further to zero if measure type 6 is implemented. For this to happen, however, it is necessary to capture the emissions effectively and as centrally as possible and either invest substantially in further infrastructure, which would not make sense given the small quantities in this example or transfer the emissions via a pipeline or something similar to someone with CCUS infrastructure for emissions storage. Therefore, some other off-site measures are needed to achieve net-zero emissions (i.e., purchase of renewables and compensation).

Table 11. Exemplary scenario „On-Site" in which measures of type 1, 2 and 3 are implemented sequentially.

	Energy amount New	Energy price Reference	Energy costs New	Emission amount New	Emission price Reference	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	700	20.40	142,800	480	35.00	16,800	159,600	65,400
t_2	700	20.81	145,656	430	40.00	17,200	162,856	69,224
t_3	125	21.22	26,530	200	45.00	9,000	35,530	203,711
t_4	125	21.65	27,061	200	50.00	10,000	37,061	209,426
t_5	125	22.08	27,602	200	55.00	11,000	38,602	215,214
(…)								
t_{10}	125	24.38	30,475	200	80.00	16,000	46,475	245,324

(...)								
t_{30}	125	36.23	45,284	200	180.00	36,000	81,284	388,988

Scenario 4: Off-Site (first measure type 4, second measure type 5):

In this scenario, switching to a clean energy tariff at the end of **t_0** (type 4) leads to a reduction of emissions in **t_1**. Due to a shortage of clean energy supply, only 70 % of the energy demand can be covered by the clean energy tariff (320 tCO_2-eq instead of 600 tCO_2-eq, cf. orange in **Table 12**). The company has succeeded in identifying and supporting climate protection projects (type 5) at the end of **t_1** and receiving certified emission reductions CERs for them from **t_2** onwards (200 tCO_2-eq instead of 320 tCO_2-eq remain, cf. purple).

Table 12. Exemplary scenario „Off-Site“ in which measures of type 4 and 5 are implemented sequentially.

	Energy amount Reference	Energy price Reference	Energy costs Reference	Emission amount New	Emission price New	Emission costs New	Total Costs New	Savings (N, E, t)
	MWh	ct/kWh	EUR	tCO_2-eq	EUR/tCO_2-eq	EUR	EUR	EUR
t_0	1,000	20.00	200,000	600	30.00	18,000	218,000	0
t_1	1.000	20.40	204,000	320	35,00	11,200	215,200	9,800
t_2	1.000	20.81	208,080	320[5]	34,00	10,880	218,960	13,120
t_3	1.000	21.22	212,242	320	38,25	12,240	224,482	14,760
t_4	1.000	21.65	216,486	320	42,50	13,600	230,086	16,400
t_5	1.000	22.08	220,816	320	46,75	14,960	235,776	18,040
(...)								
t_{10}	1.000	24.38	243,799	320	68,00	21,760	265,559	26,240
(...)								
t_{30}	1.000	36.23	362,272	320	153,00	48,960	411,232	59,040

Cumulated ongoing energy and emission costs

The cumulative ongoing costs of the **Reference Scenario** form the basis for the comparison of the different scenarios. In **Table 13**, the cumulative total (ongoing) costs from **t_1** to **t_5**, as a possible internal milestone year of the company, lead to a total of 1,196,624 EUR. The cumulative total costs after 10 years (**$t_{milestone}$**), as a possible political milestone year, amount to 2,578,743 EUR and after 30 years (**$t_{net\text{-}zero}$**), as a possible political target year for net-zero, add up to a total of 10,210,888 EUR.

In the scenarios 1, 2, 3 and 4, 200 tCO_2-eq remain in **t_2** (**t_3** for scenario 3). The measures are implemented within only 3 years and after 5 years savings of up to around 700,000 EUR are possible. If we also consider the period of 10 years, savings of up to around 1,900,000 EUR are possible. Over 30 years, the savings increase to more than 8,000,000 EUR. So if the measures require investments of around 500,000 EUR, the payback is achieved within less than 5 years and the implementation of the measures is more than profitable in the long term.

Table 13. Comparison of overall costs and savings of the scenarios 1, 2, 3 and 4 compared to the reference scenario.

	Total (ongoing) costs [EUR]			Savings [EUR]		
	$t_1 - t_5$	$t_1 - t_{10}$	$t_1 - t_{30}$	$t_1 - t_5$	$t_1 - t_{10}$	$t_1 - t_{30}$
Reference scenario	1,196,624	2,578,743	10,210,888	0	0	0
Scenario 1	797,937	1,688,420	6,447,922	398,687	890,323	3,762,966
Scenario 2	853,537	1,744,020	6,503,522	343,087	834,723	3,707,366
Scenario 3	433,649	650,164	1,935,432	762,975	1,928,579	8,275,456
Scenario 4	1,124,504	2,391,823	9,154,768	72,120	186,920	1,056,120

[5] 120 of the 320 tonnes are compensated at a price of 34 EUR per tCO_2-eq (in **t_2**). Although 320 tonnes are still emitted, only 200 tonnes (charged at the reference price) remain uncompensated.

When comparing the different savings of the four scenarios, it is vital to think about the selection (type 1 measures reduce energy consumption and emissions and thus lead to higher savings than type 4 or 5 measures, which only lead to emission reductions) as well as the order of the measures to be implemented (higher savings can be achieved by preferentially implementing type 1 measures).

If we look at the (total) remaining energy demand (in MWh) and the remaining emissions (tCO_2-eq) in the example calculations for the 6 types of measures, instead of the quantities affected by the measures (cf. dark blue in **Table 14**, i.e. taking into account also the “untouched”, remaining quantities), three groups can be distinguished: Reduction in both energy and emissions (type 1), reduction in emissions (types 2, 3 and 4) and no reduction (types 5 and 6). For type 2, other assumptions could be made so that it can fall into any of the three groups. With the exception of type 2, the three categories happen to correspond to the three categories described in **section 2**.

Table 14. Effect of measure types on energy and emission amounts

	Energy amount [MWh]		Emission amount [tCO_2-eq]	
	(total) remaining	for calculation	(total) remaining	for calculation
Reference Scenario	1.000		600	
Measure type 1	700		480	
Measure type 2	1.000		550	
Measure type 3	1.000	500	400	
Measure type 4	1.000		200	
Measure type 5	1.000		600	
Measure type 6	1.000		600	400

In all scenarios, a residual amount of 200 tCO_2-eq remains. Combining the ecological-economic effect (**Table 13**) and the influence of the types of measures (**Table 14**), the strategy is to first implement reduction measures (Type 1), then substitution measures (Types 3 and 4) and finally compensation measures (Types 5 and 6).

As energy and emission prices rise over time, off-site measures with ongoing costs become increasingly more expensive per tonne saved than on-site measures with a one-off investment. This means that it makes sense to ensure (through measures 1-3 and possibly 6) that the shares of type 4 and 5 measures that are unavoidable for achieving and maintaining net-zero emissions decrease over time.

5.6 Expenditure

Despite the savings examined in the previous sections, it must be recognised that measure types 1, 2, 3 and 6 require one-off investments (and possibly additional ongoing costs) that have to be deducted from the savings. This is addressed in more detail in this section.

As illustrated in **Equation 2**, the investment costs (**Investment(N)**) consist of both acquisition costs (**costs $_{acquisition}$**) and ongoing costs (such as operation, maintenance, etc., **costs $_{ongoing}$**). The temporal component is integrated in both parts of the formula, as the costs for acquisition may not only be incurred at the beginning **t $_1$**, but also later, depending on the period of use (useful life) **(N)**.

Equation 2. Calculation of aggregated investments for a measure option

$$Investment\ (N) = \sum_{t=1}^{N} costs_{acquisition}(t) + \sum_{t=1}^{N} costs_{ongoing}(t)$$

To economically assess a measure, both expenditure and revenue (here: savings, cf. **Equation 1**) have to be considered. Therefore, the first step is to calculate the **Investment (N)** for the implementation of the considered measure option as well as the resulting energy and emissions **Savings (N, E)** if the measure was implemented. The second step is to calculate the difference: **Savings (N, E) - Investment (N)**.

In principle, a measure is economically viable if the total savings of a measure (**savings (N, °E)**) minus the costs of a measure (**Invest (N)**) are larger than zero *within the period of use of the measure* **(N)** (cf. **Equation 3**).

Equation 3. Determining economic viability for a measure option within period of use.

$$Savings\ (N,\ E) - Investment\ (N)\ \geq 0$$

The point in time, when the difference reaches zero (breakeven) is defined as the adjusted payback time $\mathbf{t_{adj.payback}}$ (cf. **Equation 4**):

Equation 4. Determining the adjusted payback time.

$$Savings\ \left(t_{adj.payback},\ E\right) - Investment\ \left(t_{adj.payback}\right)\ = 0$$

If the payback period $\mathbf{t_{adj.payback}}$ is shorter than the period of use **(N)**, the measure is economically viable. The net savings of the measure up to a certain point in time ($\mathbf{t_x}$) can be determined by subtracting the cumulated investments (and associated transaction and measure-related ongoing costs) from the cumulated savings up to the desired point in time $\mathbf{t_x}$ and comparing the result to the Reference Scenario up to $\mathbf{t_x}$ (cf. **Equation 5**)

Equation 5. Determining the net savings in (t), provided t < N

$$net\ savings\ (t) = Savings\ (t,\ E) - Investment\ (t) > 0\ ; \quad t < N$$

The economic efficiency calculation presented here for the assessment of measures represents a minimum requirement that takes two aspects into account. On the one hand, it considers the period of use (and not only the payback period as the sole decision criterion) and, on the other hand, the temporal component (and thus the changes in energy and emission prices as well as energy and emission quantities). The latter allows one to assess the economic performance over time, such as savings and/or additional expenditures (i.e., for replacements).

5.7 Selection of measures: combining economic efficiency and system view

Looking at the different scenarios and comparing their outcomes, as discussed in **sections 5.3-5.5** and highlighted in **Table 13**, it makes sense to prioritise on-site actions (1, 2, 3, 6). It is crucial to keep an eye on the economic factors, but also on all external factors, and to act quickly if one wants to (a) build resilience against availability-, price- and other shocks, (b) reduce the risk of having to wait in line, and (c) minimise the “procrastination costs” of missed savings opportunities.

The latter illustrate that a “good” choice of measures is also subject to temporal changes: If climate neutrality is to be achieved in the short term, it makes sense to focus on measures (4) and (5). In order to minimise the costs of climate neutrality and build resilience, it is advisable to initiate accompanying local efficiency measures (1) and on-site energy generation (3). These have a longer implementation horizon but generate the savings that then allow one to initiate measures against (2) or to capture (6) (process) emissions and finally to reduce the purchase of energy from external sources (4) and offsets (5) (cf. **Figure 5**).

Bosch has taken a similar approach to become CO_2-neutral within 18 months. At least half of the two billion euros invested for this purpose will have paid themselves off by 2030 through the savings from (1), (2) and (3) [73]. The pay-off of the decisions taken could be even higher: Firstly, the European emissions price ETS has more than doubled since May 2019 [62], secondly, a national emissions price has now been introduced in Germany for energy sources that do not fall under the European Emissions Trading Scheme ETS [68], thirdly, the European Union is further tightening the ETS and extending it to energy sources beyond electricity [74,75], and fourthly, the social trend towards climate neutrality has become increasingly influential [12].

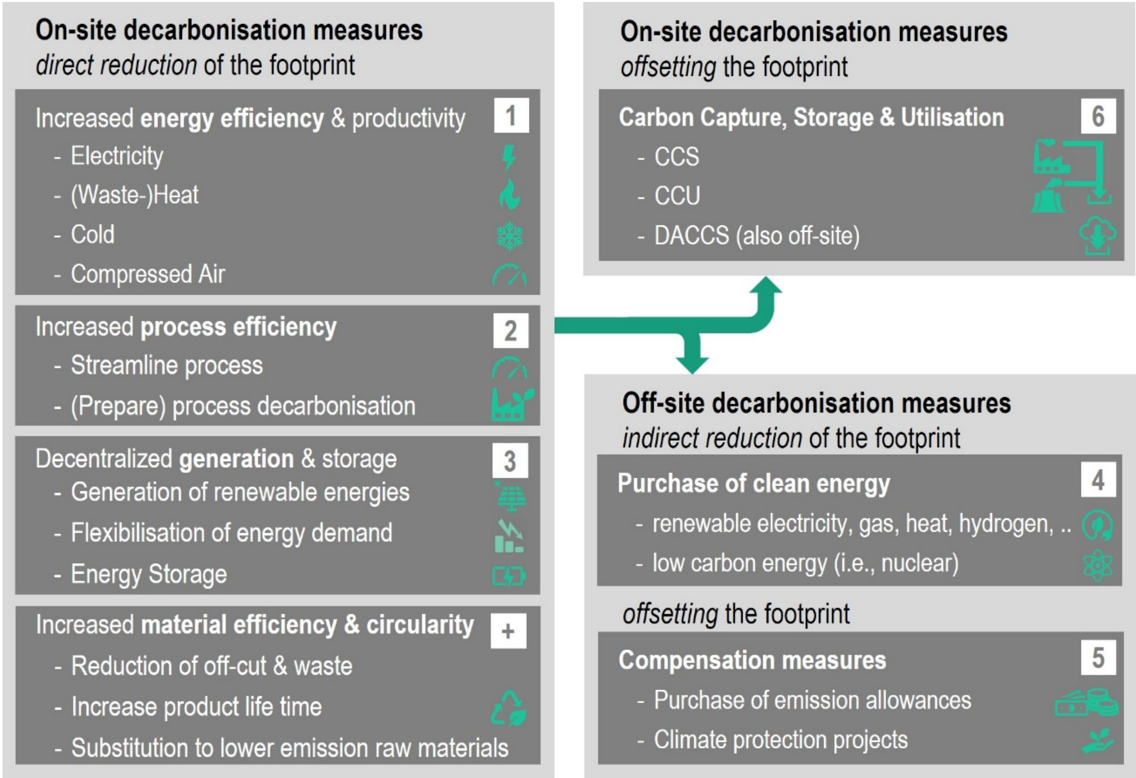

Figure 55. On-site and Off-site decarbonisation measures (own illustration based on EEP/Fraunhofer IPA)

5.8 Creating a ranking system to determine one's ideal mix of measures

To determine a mix of measures, ideal to one's situation, not only the **economic performance of theoretically suitable measures** is of relevance. As important as the economic performance of a measure in relation to the envisaged intermediate- and target year is how:

a) it fits into the general (decarbonisation) strategy of the company, notably the **reason why** decarbonisation is pursued,

b) it performs in respect to the company's **decision-making determinants** and

c) its impact depends/builds on and **interacts**/is **compatible with other measures**,

d) it contributes to company risks, production **risks or resilience** (if at all), and how

e) effective it is to reach the **ambition level** (certain GHG savings by certain time).

Buettner describes seven steps to identify a decarbonisation strategy: chief among these are the establishment of clarity regarding the target dimension, the goal, the timeframe, the area of observation and particularly the 'why' – the motivation for doing so [76]. Motivators can be: long-term economic advantages, corporate social responsibility, reduction of cost risk, customer requirements, image improvement, government or investor requirements [12]. As numerous of the points **(a-e)** relate to the company strategy, **(a)** primarily refers to how well a measure serves the (primary) motivators of the company.

Decision-making determinants **(b)** include: the costs per avoided tonne of CO_2-eq or cost per kW_p (Kilowatt peak) of energy generation capacity, or per kWh saved, the level of investment, technical aspects, implementation competence, and, overlapping with the motivators, also expected increase in productivity and image effects [4].

Especially in times of crisis, uncertainty, and vulnerable supply chains, but also more generally when a needed commodity is in short supply, it can play an important role whether and in which way a measure **increases or decreases risks or resilience** of a company (or its production) **(d)**. This resilience, for instance, can be achieved by prioritising on-site measures as they reduce dependency on others or by diversifying supply. For the latter, a company should either work towards a flexibility in respect to the energy source (i.e., bivalence, allowing processes to be powered by two different types of energy), the supplier of energy, or the type and location of self-generation of energy).

The **level of ambition (e)** influences whether measures can be undertaken in sequence to optimise for the most cost-effective mix, or whether measures of a similar type need to run in parallel, reducing the cost-effectiveness, but allowing quick(er) achievement of the net zero goal. The path of quickly achieving net zero, for instance, was chosen by Bosch, which simultaneously undertook many types of measures to reach net zero in a very short period. However, this achievement also required compensation and the purchase of green energy while energy efficiency measures, self-generation, etc. were put in place, gradually allowing the company to scale down their compensation and purchasing efforts [73].

This notion as well as changing environments, respectively external effects, can considerably change the situation and subsequently the overall "value" and performance of a measure. Therefore, it is advisable to mirror the calculation model introduced above (cf. **sections 5.1 and 5.6**) into a digital model into which the figures and values are entered for the both the individual measures, but also the overall considerations. If connected to external sources, such as energy and emission market figures or their respective forecasts, the system could constantly update the ranking of measures (in consideration of those already implemented).

To enable such a ranking, it is necessary to introduce a scoring model that reflects all ingredients (i.e., **a-e** above) that are of relevance in the company's decision-making process. In the context of this report, such a model may include binary (yes/no), scaled/ordinal (from low to high or negative to positive), nominal (i.e., different applicable characteristics) or metric (i.e. amount of investment or useful life) variables. Such variables, especially nominal ones, allow measures to be ranked by category – i.e., measures addressing process emissions, versus measures addressing energy-related emissions. Filters in metric variables allow one to, for example, exclude measures whose investment level is too high (i.e., exceeds own budget) or which are too expensive per unit of energy/emissions saved. As highlighted in **section 1.4**, spatial, technical or strategic aspects may lead to a pre-selection or the exclusion of some conceivable measures. Indeed, some companies exclude certain measures such as offsets in principle, whereas others may not have the space for on-site renewables or refrain from technical interventions that would endanger product quality or process stability. For measures that are excluded from the outset for these reasons the assessment procedure described in **sections 5.1-5.8** should not be carried out. However, it should be applied to all remaining conceivable, individual measures.

All binary, ordinal and metric variables, including the score, can be used to rank the remaining measures according to this variable. A weighting factor can be introduced to assign different levels of importance to the variables, which then influence the score of a measure and subsequently its rank in the ranking (see exemplary depiction in **Table 15** in combination with **Table 16**).
In summary, this means that the model described can be mathematically optimised for individual or combinations of aspects (i.e., quickest or cheapest decarbonisation, highest resilience, etc). As scoring models are a much-researched topic [77,78], this report does not go into further detail on these.

Table 15. Possible indicators of a scoring model / table (by variable type)

metric (years)	metric (figures)	binary or ordinal	nominal	filter
useful life	net savings (t)	impact on resilience	type of measure	on-/off-site measure
intermediate target	investment height	risk of failure/to operations	requirement for measure	investment < ...
target year	GHG savings	addressing motivators	type of emission addressed	cost per … < ...
adjusted payback time	*rank*	meeting decision criterion	scope addressed	skills exist
…	*weighting factor*	fits to strategy	description of measure	net savings (t) > 0
	score	…	...	adj.PT < useful life
	…			…
Definitions			**optimise for (i.e.)**	
∑(weighting factors) =! 1		z = number of measures	goal achieved cheapest [or quickest]	
Score = ∑(weighting factor x measure score), the higher the better			best impact on ... (resilience, image, risk, strategy, ..)	

It is not unlikely that there are measures, which are actually economic, but whose useful life is shorter than the time span until the milestone year. Therefore, an assessment of all economic measures is necessary to compile the ideal mix of measures for achieving the intermediate objectives (i.e., a certain reduction target by 2030), the overall objective (i.e., achieving net-zero by 2040), but also for sustaining the desired outcome (i.e., maintaining a net-zero emission footprint infinitively), taking into account useful lives and changing prices.

Table 16. Exemplary shape of ranking table extract (random figures)

Target Year 20XX Milestone Target Year 20YY

Measure	Type	Score	Rank	meeting decision criterion [Filter]	impact on resilience	address-ing motiva-tor	figure of numeric decision criterion	**net sav-ings (t)**	GHG saved p.a.	…	depends on
Description	1-6	metric	[1 … z]	[0 ; 1]	[-1 ; 0 ; 1]	[0 … 5]	metric	metric	metric	…	
Example using random figures				cost per tonne saved < 150€/t_{CO2}		image	cost per tonne saved		energy-related t $_{CO2eq}$	…	
Weighting Factor					*20%*	*10%*	*15%*	*25%*	*30%*		
Solar PV	3	25.3	1	1	1	5	119.00 €	100,812 €	200	…	(roof)space
Green Tariff	4	22.6	2	1	-1	3	2.65 €	90,000 €	400	…	availability
EE-Measure	1	11.4	3	1	1	4	125.00 €	45,487 €	120	…	skill
CO_2-allowance	5	10.9	4	1	0	0	45.00 €	43,300 €	200	…	availability
ProcessDecarb.	2	-47.2	5	0	0	3	200.00 €	- 188,750 €	0	…	skill
CCUS	6	-238.7	6	0	0	1	250.00 €	- 955,000 €	0	…	regulation

Table 16 shows an extract from a ranking table using random numbers. It lists the economic performance according to the above formulas in t = 5, assuming a period of use of about 20 years per implemented measure and a mark-up of 1 % for the use of renewable energy. Apart from this, the assumptions and figures of the previous sections apply. As highlighted in **Table 14**, the different types of measures affect the net GHG footprint in different ways, sometimes directly, sometimes indirectly. In the case of measures that primarily aim to reduce the amount of energy purchased (types 1 and 3), the saving in energy costs is the decisive factor. The amount of the reduction in greenhouse gas emissions that occurs as a side effect also depends primarily on the emission content of the (previous) energy source and says little about the quality of the measure. If only the CO_2 avoidance costs are considered, these measures appear excessively expensive, which is why the cost per kWh saved or kWh generated must also be taken into account in a complete ranking. Therefore, energy- and emission cost savings should always be considered and compared with the compatible action alternatives. The principle applies equally to the saved process emissions per year (types 2 and 6) and the consideration of the estimated financial performance for several points in time (**t_x**) (e.g. **$t_{milestone}$, N**) instead of just one (see **Table 15**).

Measure types 2 and 6 illustrate that treating process emissions can be quite costly. However, if measure 2 takes place in the context of a replacement investment for machinery, the cost of the measure is only the price difference between the “standard replacement” and the lower emission process technology, thus reducing the investment cost and improving the financial performance of the measure. As CCUS works best at emission-intensive sites for processes with high emission concentrations (figuratively speaking: sticking the technology on the exhaust), it makes more sense for larger emitters. However, measure types 2 and 6, together with some related technologies, are the only means to “actually” address process emissions in the long term [39].

6. Conclusion

Depending on the nature of one's own economic activity, above all how energy- and emission-intensive one's own company is, how large it is and how far into the future one plans, the one-off and the permanent (ongoing) costs play a different role. Moreover, this *role can change over time.* For example, if the framework conditions change or if the most cost-effective measures have been implemented but the emission reduction target has not yet been reached.

The economic efficiency calculations of the individual measures should then be evaluated and prioritised, taking into account the exposure of each type of measure to fluctuating energy and emission prices. The calculations described would need to be *carried out for all available alternative actions* - i.e., individual measures or interconnected groups of measures - in order to determine the most economic mix of measures *at that time*.

Due to the variability of energy and emission prices and the effort required to evaluate the possible alternative actions, it makes sense to *map* the described economic aspects together with technical and other influencing factors in a spreadsheet or, *ideally, in a digital model*. Only in this way is it possible to consider the (remaining) options for measures dynamically, to optimise them for the target time and update them over time, as well as to rank them according to the most economic combination of measures.

Often there is a set of intermediate targets and associated timetables: internally, this is at least the year in which the target emission level is to be achieved (t_{target}), often supplemented by intermediate milestone years and emission levels ($t_{milestone}$). However, political milestones are also of great importance. Many countries and regions have set intermediate targets for 2030 ($t_{intermediate}$) and aim to achieve net-zero emissions by 2050 ($t_{net\text{-}zero}$) at the latest. In view of a rapidly changing environment and in order to enable comparability with conventional economic efficiency calculations, it makes sense to also include the first three years after the start (t_2, t_3 and t_4) in this consideration. An ideal mix cannot be static, it evolves over time and should especially take into account the financial performance of the selected measures up to the internally determined target year ($t_{net\text{-}zero}$), as well as the intermediate political milestone year (i.e., 2030). This avoids choosing a mix that turns out to be very costly in the long run, while ensuring that measures are implemented which are economically superior from the perspective of the target year(s) but would not have been chosen under conventional calculation approaches.

It is important to remember that reaching the desired target does not mean it ends there. Like the "desired weight" that must be maintained after it has been reached, the net-zero state needs to be maintained over time as well. This may require changing the mix of measures in light of technological change and replacement needs energy- and emission prices, resilience and other considerations, including new/revised internal or external targets or requirements. The formulas and mechanisms introduced in this report can support this continuous process.

Furthermore, one should note that *prices, policies and availabilities differ greatly across the world*: not only electricity is priced very differently across countries, but also the price ratios between electricity, gas and other forms of energy can differ substantially (due to subsidies, taxes applied, ease of acquisition and supply). Similarly, emission factors may vary markedly depending on the energy-mix. There are regions with and without emission charges on different energy carriers, and in all or just some sectors. The state of the infrastructure, regulations, availability of skilled labour or simply access to technology determine whether measures can be implemented at all. Moreover, they can expand the range of feasible measures, but they can also limit them. Additionally, the approaches taken by policymakers and the political systems differ. In consequence, the economic viability of the same measure may be very different across countries and the acquisition costs may pay off easily in one region and not during the useful life of the measure in another.

Nevertheless, the principles described in this report, particularly *the formulas, are robust against these differences* and can be applied irrespective of different realities, be it geographical, political or any other dimensions. Indeed, the figures can be very different, and the resulting ranking order may highlight a very different set of measures, but the formula into which the figures are entered does not change. If, for instance, there is no emission price in one region a “0” is entered into the formula to account for the emission cost of the Reference Scenario. Similarly, other factors could be non-existent (‘0’), constant (‘1’), increase/decrease or vary. The functionality of the formula is not affected.

This creates a *scientifically and technically sound decision-making and planning tool* for short- to long-term monitoring and impact assessment that also takes into account the factors that can be influenced to a greater or lesser extent. For example, assume that the production processes are adjusted in terms of time and quantity to the availability of renewable energy. In that case, procurement can be optimised and a contribution can be made to grid stability [27].

Considering the measures, interdependencies, and calculation methods described the possibility of quasi-dynamically *determining the most economic mix of measures for net-zero emissions is within reach* if digital mapping is used.

Applying the principles and determinants described in this report for one’s economic assessment of industrial decarbonisation measures should hence allow one to determine one’s optimal pathway to reducing the greenhouse gas footprint in manufacturing (and beyond).

Author Contributions: Conceptualization, S.M.B.; methodology, S.M.B. and D.W.; formal analysis, D.W. and S.M.B.; investigation, S.M.B. and D.W.; writing—original draft preparation, S.M.B. and D.W.; writing—review and editing, S.M.B. and D.W.; visualization, S.M.B. and D.W.; supervision, S.M.B.; project administration, S.M.B.; funding acquisition, S.M.B. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable

Acknowledgments: This research would not have been possible without the continuous support of the Karl-Schlecht-Foundation and the Heinz und Heide Dürr Foundation, as well as those reviewing and supporting in progress of developing this report notably Marina Gilles, Igor Litvinyuk, Christian Schneider, Thomas Renaldy, Lukas Bebensee, Sebastian Trost, Sonja Ziehn, Manja Hies, Eckard Beer and Nihal Darraj.

Conflicts of Interest: The authors declare no conflict of interest.

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