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CO_2-based assessment for sustainable production planning in the metal processing industry

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Abstract

By assessing the emissions of greenhouse gases of finished goods over their entire lifecycle, it can be seen that a significant part of the emissions is caused in production and related upstream processes. A strong focus on resource-efficient production techniques could provide possibilities for significant emission reduction in these processes. This causes the need of a quantitative comparison of different production techniques and processes by their total CO_2-eq.-emissions. Especially small enterprises may not be able to provide information on energy and resource flows and resulting emissions on a level that is detailed enough to reveal emission reduction potentials.

The assessment model introduced is applicable for every enterprise to quantify production-related emissions of their finished goods and to compare them with other possible production techniques and processes, in order to facilitate CO_2-based production planning. The model is highly flexible, as calculations are based on a process database that can easily be modified. Moreover, the input of country-specific and manufacturer-specific data like country-specific electricity-mix or material-manufacturer-specific CO_2-eq.-emissions enables a high customization level.

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Keywords: Cleaner Production; Life Cycle Assessment; CO_2-eq. quantification; green supply chain; metal processing industry; sustainable production planning

1. Introduction

Most scientists agree that the massive emission of carbon dioxide (CO_2) and other greenhouse gases with is considered the main reason for the climate change the world is facing at the moment. With its “Europe 2020” strategy from 2010 the European Union set, among others, the target of reducing the emissions of greenhouse gases by 20% compared with the amount of 1990 [1]. In Germany, politicians want to achieve a reduction by even 40% until 2020

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on a national level [2]. In accordance with the rule "You cannot manage what you can't measure", it is essential to not only define quantitative aims (like in the Europe 2020 strategy) but also develop methods to measure the progress in achieving these aims [3]. Measuring an activity's greenhouse gas emissions could provide such data with a smaller scope. These results could then be aggregated up to a national level. To account for the differing impacts of greenhouse gases on climate change, all emissions are standardized to CO_2-equivalents (CO_2-eq.). To reach a significant reduction of emissions, it is important to know where most emissions are caused.

Research of the German Federal Environment Office showed that in 2014 around 20% of total emissions of CO_2-eq. in Germany were caused by industrial processes or manufacturing industries and construction [4]. On the product-level, the numbers are similar: concerning the automotive industry, the production process (in 2012) accounts for around 20% of an automobile's lifetime emissions of CO_2-eq. and will increase to 36% until 2030. For BEVs (Battery electric vehicles) in particular, in dependence of the electricity mix, the part of production related emissions could increase to 76% until 2030 [5].

2. Research Approach and Literature discussion

To achieve lower emissions in industrial processes, tools should be developed which enable the analysis of the CO_2-efficiency of manufacturing chains. Those tools could at first quantify the emissions caused by the production of a good and furthermore help improve the production chain from an ecological point of view by identifying high-emission processes. A strong focus on resource-efficient production techniques could provide possibilities for significant emission reduction in these processes. Given several possible materials and alternative manufacturing chains to produce the same products, such a tool could identify the ecologically favorable one and help to integrate ecological aspects in the decision-taking process.

Common eco-balancing software like GaBi [6], Umberto [7] or SimaPro [8] aim for a lifecycle assessment (LCA) from cradle to grave and require a large amount of accurate data to run a satisfying analysis. The big effort that is necessary for such an analysis may have a deterring effect, especially on small and medium enterprises. Tools that focus only on the emissions caused by the production and upstream processes do require a much lower effort for collecting data and modeling the production processes. Due to the focus on the manufacturing chain only, the results of their analysis may have more practical relevance for operative or tactical decision-taking in the production environment (e.g. decision about which production technique to choose) than the results of complex LCA-software.

A first generic tool for ecological production chain analysis called BEATool has been developed in the BEAT-project, supported by the German Federal Ministry of Education and Research, the Daimler AG and the Robert Bosch GmbH, among others [9].

The BEATool models manufacturing chains using generic machines with predefined input/output parameters and central units (e.g. water cleaning unit) whose services are demanded by various generic machines. The assessment of the modeled production process is realized by the integrated GaBi5 database. The BEATool allows to enter up to 15 generic machines and to compare two alternative production techniques by their effects on the environment [9].

To allow a more detailed CO_2-calculation, further processes of the production chain have to be taken into account, such as recycling and transportation processes for material that is used as well as supplier-specific CO_2-eq. emissions for material-production and country specific emissions for energy supply. To consider all relevant emission-based processes, we developed a calculation-tool called TEOPP, that enables the CO_2-based assessment for sustainable production planning. We further considered a high flexibility concerning the units of input parameters that reduces the effort for further unit conversion or data recording. A fast adaption to other industry sectors and company specific needs is made possible by the integration of an easily modifiable database. Furthermore, the tool has no limitations concerning the quantity of entered processes or alternative production techniques.

3. Tool for Emission-Oriented Production Planning (TEOPP)

TEOPP is a Microsoft Excel-based application programmed in Visual Basic for Applications (VBA) that allows even technically less experienced users to work in a well-known IT environment. It focuses on the analysis of manufacturing chains and makes it possible to compare different production techniques by their emissions of CO_2-eq.

per product. The indicator of CO_2-eq. has been chosen because it values all greenhouse gas emissions appropriately and is generally known as a good indicator for an activity's effects on climate change.

In TEOPP every manufacturing chain can be modelled using three different types of processes: Production processes, recycling processes and transportation processes. Production processes represent the material treatment throughout the manufacturing chain. They are classified by their manufacturing technique, using the DIN 8580 classification in casting, forming, cutting, joining, coating, changing substance properties and washing as an additional type [10]. Production processes have one main output which is the functional unit for this process and whose CO_2-balance is calculated. This main output will then be an input for the following production process. The tool allows to enter a scrap rate for the main output and a linkage to a separately modelled recycling process that describes the handling of deficient products (e.g. melting). Each production process can be defined using a quantity of different parameters and linking them with recycling and transportation processes. Fig. 1 shows a simplified illustration of production process parameters and possible links to the other process types.

To reduce a company's effort for collecting the necessary data, the tool accepts a variety of input units. For every process a reference value can be selected. The units of all parameters of this process will strongly depend on the chosen reference. Selectable references are main outputs (possible unit: kg/piece of primary output), time / flow time (possible unit: kg/h) or production cycle (possible unit: kg/production process). If production cycle is chosen as a reference value, the tool automatically generates two different machine status (e.g. Stand-by and On work) whose parameters can be entered separately. In case of need, more machine status can be added for a more detailed process description.

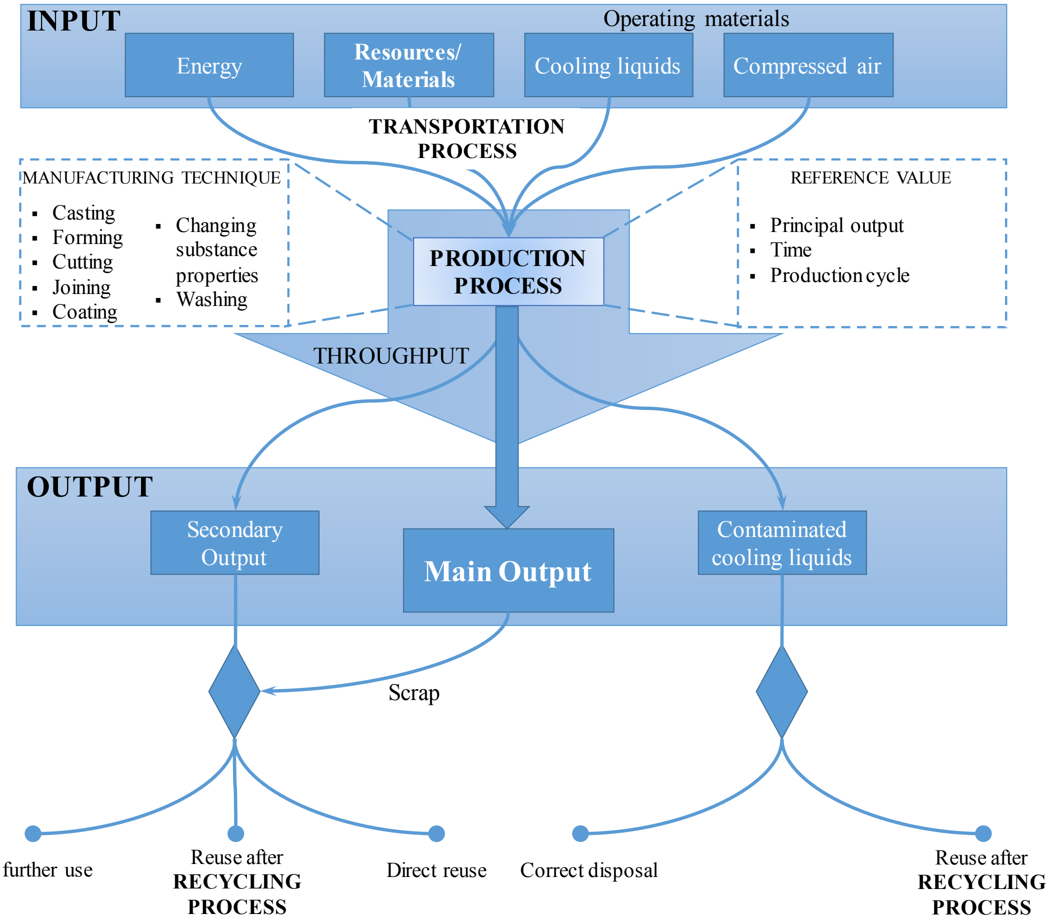

Fig. 1: Metal processing example - showing production process parameters and links to other processes

In the following, input materials and input piece goods are assigned to the process. These can be selected from outputs of previous processes or resources that are new in the analyzed manufacturing chain. A specific supplier can be selected for the input material, if a corresponding value is found in the database. The support of piece goods (e.g. 5 screws) allows a high flexibility in the entered data and a more intuitive understanding of the modeled process. Each input material and each input piece good can be linked to a transportation process. These processes represent the transportation of the resources before being handled in the analyzed manufacturing chain (e.g. transportation from suppliers to production plant). The emissions of transportation processes depend on the distance covered, the transportation mode (truck, train, inland waterway vessel, deep-sea vessel or plane) and the weight of the transported material.

The energy consumption of a production process is divided up into three different types of energy consumption: Electric energy, thermal energy (e.g. long-distance heating) and energy sources (e.g. heating by burning wood or gas). The corresponding amount of CO_2-eq.-emissions per kWh does not only depend on the energy source, but also on the country-specific electricity mix. This dependency secures the consideration of country-specific characteristics like specific energy mixes. To be able to consider this fact in its calculations, TEOPP asks for every energy consumption linked to a production process to declare the country of origin.

Furthermore, compressed air consumption and a quantity of different operating materials and cooling liquids can be assigned to each process. For each of those, a recycling treatment in the form of a separate recycling process (e.g. wastewater treatment) can be defined.

In addition to the above described main output, the declaration of additional secondary outputs such as chips or other recyclable or non-recyclable waste is supported by TEOPP. For each secondary output details about downstream treatment can be described. Depending on the following output use, secondary outputs are positively considered in the emission balance. The following handling might be a direct reuse in another process, reuse after going through a recycling process (e.g. melting of metal chips) or no further use. If the secondary output is recycled, it can be linked to a recycling process whose parameters are set separately.

Like production processes, recycling processes do have material, energy, compressed air consumption and cooling liquid inputs. Instead of a main output parameter they include a parameter to declare the recycled material. The declaration of secondary outputs is also possible for recycling processes. Apart from the parameter "main output", the main difference in the characteristics of production processes and recycling processes is that the latter are not allowed to be linked to other recycling processes.

To enable accurate calculations, the TEOPP includes a database that allows to rate all material and energy flows by their emissions of CO_2-eq. It is based on the EcoInvent database [11] and completed with supplier- and production-site-specific CO_2-Emissions for the steel-production. For every other relevant material, average values for the emissions caused by their production are declared. The data in the database is strongly geared towards the needs of the metal-processing industry. The database is highly flexible, so that the tool can easily be adjusted to other industry sectors or company-specific needs. It is easily possible to add new materials, update existing values or enter supplier-specific emission values for further resources. This flexibility allows a fast customization of the tool and a nearly unlimited range of application in the entire production industry.

4. Formal model formulation

The CO_2-eq. balance is based on calculations that use the information about the manufacturing chain, provided by the user and the data from the database that quantifies the emissions of the modeled energy and material flows. The following section describes the most important part-calculations and the calculation methods the tool uses to quantify the emissions of a product in CO_2-eq. given all production processes numbered $i=1,\dots,n$ chronologically in the order of their impact on the produced good. Production process n will then be the end of the manufacturing chain and the main output of production process n will be the main output of the entire manufacturing chain and as such, the object of interest for the balance calculation. As all processes will in one kind or another use the output of upstream processes, the balance of the last process's main output B_n can only be calculated given a balance for the output of the upstream process B_{n-1}. This results in an iterative calculation of B_n as shown in Fig. 2.

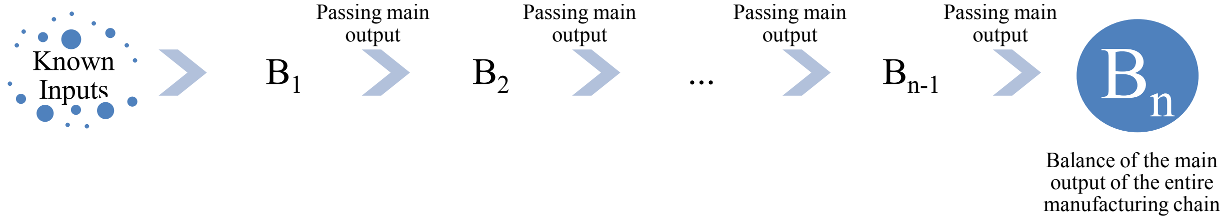

Fig. 2: Balance calculation scheme (simplified representation)

The balances of upstream processes can be calculated valuing the input/output material and energy flows. The total amount of emissions per main output can be divided up into the factors material input, energy, cooling liquids and operating materials, compressed air and secondary outputs. As mentioned before, the latter usually have a positive, means diminishing impact on the emission-balance. Given these influences the formula for the balance of the main output of production process i results in:

$$B_i = B_{material\ input,i} + B_{energy,i} + B_{cooling\ liquids,i} + B_{compressed\ air,i} + B_{secondary\ output,i} \quad (1)$$

$$\text{, usually with } B_{secondary\ output,i} \leq 0 \ \ \forall i \in \{1, \ldots, n\}$$

The balance is always calculated in CO_2-eq. emissions per one unit of the main output (kg, l or piece) so that it is invariant to the quantity of produced goods. The part of the balance that is due to the input material can be split up into the emissions of the production of the material and the emissions caused by its transportation to the manufacturing plant. The part-balance for the material results in:

$$B_{material\ input,i} = \sum_{r_i=1}^{l} M_{r_i} \times u_{r_i} + \sum_{r_i=1}^{l} \left(d_{r_i} \times u_{t_{r_i}} \times \frac{M_{r_i}}{1000} \times [(\mathbb{1}_{e_{r_i}=1} \times e_{r_i}) + (\mathbb{1}_{e_{r_i}=2} \times \rho_{r_i}) + (\mathbb{1}_{e_{r_i}=3} \times m_{r_i})] \right) \quad (2)$$

$\{1, \ldots, l\}$: *Input material of production process i (material or piece good)*

M_{r_i}: *Quantity of the material input* $(in\ unit\ e_{r_i})$ *per unit principal output*

e_{r_i}: *Unit of the material input, with* $e_{r_i} = \begin{cases} 1, & raw\ material\ in\ kg \\ 2, & raw\ material\ in\ l \\ 3, & input\ piece\ good\ in\ piece \end{cases}$

ρ_{r_i}: *Density of material* r_i *in* $\frac{kg}{l}$

m_{r_i}: *Mass of input piece good* r_i *in kg*

u_{r_i}: *Conversion factor for material* r_i *in* $\frac{kg\ CO_2 - eq.}{unit\ of\ the\ mat.}$

d_{r_i}: *Transportation distance of material* r_i *before usage in manufactoring plant*

$t = 1, \ldots, 5$: *Possible modes of transportation (truck, train, inland waterway vessel, deep − sea vessel or plane)*

u_t: *Conversion factor for transport in dependency of the transportation mode t in* $\frac{kg\ CO_2 - eq.}{tkm}$

t_{r_i}: *Transportation mode by which material* r_i *is transported before being processed*

The effect of secondary outputs on the balance depends on whether they need to be recycled before their reuse or not. Secondary outputs can either not be used any more, reused directly or reused after a recycling procedure. The part-balance for the secondary output results in:

$$B_{secondary\ output,i} = \sum_s(-S_{i,s} \times u_s \times \mathbb{1}_{e_{i,s}\geq 1}) + \sum_s(S_{i,s} \times R_{i,s} \times \mathbb{1}_{e_{i,s}=1})$$
(3)

$S_{i,s}$: $Quantity\ of\ secondary\ output\ of\ material\ s, that\ results\ from\ the\ production\ of\ one\ unit\ of\ the\ principal\ output\ of\ production\ process\ i$

$e_{i,s}$: $Handling\ of\ the\ secondary\ output\ s\ from\ production\ process\ i\ with\ e_{i,s} = \begin{cases} 2, & Reuse\ after\ recycling \\ 1, & Reuse\ without\ recycling \\ 0, & No\ futher\ use \end{cases}$

u_s: $Conversion\ factor\ for\ secondary\ output\ s\ in\ \frac{kg\ CO_2 - eq.}{unit\ of\ s}$

$R_{i,s}$: $Eco\ balance\ for\ the\ recycling\ of\ one\ unit\ of\ secondary\ output\ s\ with\ recycling\ process\ r_{i,s}$

In case of no further use, the secondary output does not have any positive impact on the balance ($B_{secondary\ output} = 0$). If the secondary output can directly be reused, the entire ecological value of the material is positively considered in the balance ($B_{secondary\ output} = -S_{i,s} \times u_s \leq 0$). If a recycling process is needed before reusing the material, the ecological effort for the recycling process needs to be subtracted from the ecological value of the material before considering it in the balance ($B_{secondary\ output} = -S_{i,s} \times u_s + S_{i,s} \times R_{i,s}$).

5. Evaluation methods

The tool allows to quantify the emissions of a production system and to compare different production techniques by their emissions of CO_2-eq. There are various focuses for evaluations available: production techniques will at first be compared by their total amount of emissions. They can then be compared by the emissions of their processes, by their input parameters over the entire production cycle or by the emissions grouped by manufacturing techniques. In addition, the percentage of emissions that is caused by the material itself (without the emissions caused by the production process) is calculated and shown graphically. All evaluations are shown in meaningful diagrams and saved in an automatically generated PowerPoint file. Fig. 3 shows some of the TEOPP evaluation diagrams. The three analyzed production techniques produce the same product and consist of a casting process, a material pre-treatment process and a washing process. The washing temperature depends on the material pre-treatment. A lower washing temperature requires a more complex material pre-treatment. The analysis shows that production technique 3 with the most complex material pre-treatment and the lowest washing temperature is the best choice regarding the total emissions. Although the emissions caused by compressed air and cooling liquids in the material pre-treatment are higher than in the other processes, the amount of total emissions is lower because of the energy-savings in the washing process.

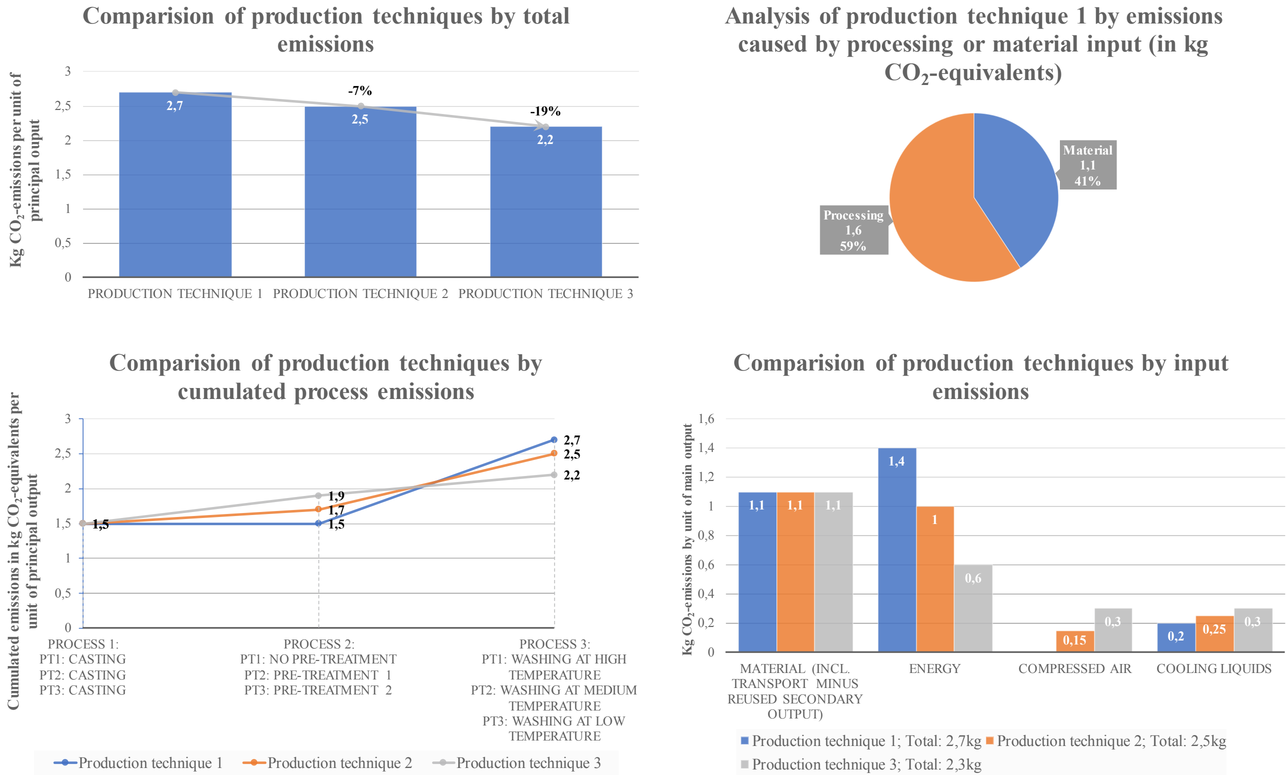

Fig. 3: Presentation of results (overview)

These results of the analysis can then be passed to decision-taking company units as decision-support and they might be considered for CO_2-based production planning. This enables the integration of ecological aspects into the decision-taking process, regarding production-related questions. First, the tool allows to quantify the emissions of an existing production system and to analyze the effects of possible changes in the system (e.g. the installation of a new milling machine that needs less cooling liquids). Given a product that can be produced by various production techniques, the tool helps to compare them and identify the best one from an ecological point of view. The quantification also enables to measure the progress in achieving emission-based targets. The evaluation based on the emissions of the modeled processes shows which parts of the entire production process have the most influence on the total amount of emissions. A stronger focus might be put on these processes when looking for more emission-efficient technologies in the market. Furthermore, TEOPP allows companies to analyze and quantify the impact of the suppliers-choice on the emissions of their product during the production process. In the last analysis, the tool shows what part of the total emissions is caused by material production in upstream processes of the analyzed manufacturing chain. A high result in this analysis may in some cases be a signal to look for alternative materials with a better eco balance and as little further effects on other product characteristics as possible.

6. Summary and Discussion

Although TEOPP does not reflect all the information that is necessary to calculate an exact carbon footprint of the product (e.g. machine wear), it provides a detailed CO_2-eq. estimation and a base for further investigation and analysis. The TEOPP accepts a wide range of parameters and input units, including transportation and recycling processes and supplier specific data. The possibility to compare alternative production techniques enables an integration of the ecological point of view into the production-related decision-taking process. The high quantity of customization possibilities allows a fast adaption to other sectors of the manufacturing industry and to company-specific needs (e.g. by inserting more material-supplier-specific emission data). The more manufacturer-specific data is provided in the database, the more exact the results of the assessment model will be. The developed tool is transferable and generally applicable for CO2-balancing of the production/manufacturing of other industries as well, but in this case it would not be material-supplier-specific anymore. To provide material-supplied-specific evaluation/assessment, the underlying database in the tool would require updating.

TEOPP will be applied in a case study in the future. Further research aims for more manufacturer-specific emission data for other raw materials like aluminum and several polymers that will be integrated in the TEOPP database. Furthermore, the further development of the tool will include costs for the different production techniques. This will result in an estimate of the investment that would be necessary to reduce the emissions caused by the production of a certain quantity.

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