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Thermochemical recycling of plastics – Modeling the implications for the electricity system

Alla Toktarova *, Lisa Göransson, Henrik Thunman, Filip Johnsson

Department of Space, Earth and Environment, Energy Technology, Chalmers University of Technology, Gothenburg, Sweden

A R T I C L E I N F O

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A B S T R A C T

To achieve a circular economy, we need to reinvent the ways in which plastic products are produced, used and recycled. This study investigates the cost-optimal design and operation of an electrified process for the production of plastics that employs thermochemical recycling of plastics and waste. In addition, the impact of this process on the north European electricity system is investigated. A techno-economic optimization model, with the objective of meeting the demand for electricity and plastic to the lowest cost, is developed. The model minimizes the investment and operating costs of electricity and plastic production units while meeting the demands for electricity and plastics without adding carbon-dioxide to the atmosphere. The model considers different flexibility options that can be applied in the plastics production process.

A fully flexible plastics production process that has flexibility in relation to time, location and CO_2 utilization shows the lowest cost for plastics production and the highest carbon circularity. At the same time, a fully flexible process has the lowest capacity utilization rate, i.e., there is an investment in overcapacity. The results show that a process with flexibility in time renders 100% carbon recovery beneficial, whereas inflexible operation of the plastics production process requires the development and scaling-up of carbon capture and storage facilities. Furthermore, the results show that for the thermochemical production of plastics, the availability of large volumes of waste and favorable conditions for generating electricity at low cost determine the location of the plastics production units. The additional electricity demand to produce plastics is mainly covered by increased generation from wind and nuclear power plants, while wind and solar power dominate in the modeled electricity system mix.

1. Introduction

Direct CO_2 emissions from primary chemical production account for 15% (923 $MtCO_2$/year) of global industrial CO_2 emissions. High-value chemicals (HVCs) contribute 27% of the primary chemicals' CO_2 emissions (IEA, 2022). The majority of HVCs are used to produce plastics, such as ethylene and propylene, and are derived from fossil hydrocarbons. Plastic is a ubiquitous material in modern society. Europe is the fourth largest producer of plastics globally, manufacturing 55 Mt of plastics (in Year, 2020), which requires around 47 Mt carbon. In general, plastics are distributed across three fractions: plastics in use; post-consumer managed plastic waste (recycling, incineration, and landfill); and mismanaged plastic waste (Geyer et al., 2017). The low degree of circularity and the accumulation of mismanaged plastic waste in the environment are global growing concerns.

The plastics recycling sector in Europe is undeveloped and fragmented, even though it has a potentially high value (Milios et al., 2018). In the EU in 2019, 14% of plastic waste was recycled, 37% was sent for landfilling, 44% was sent to energy recovery operations, and 5% evaded waste management systems (i.e., mismanaged and littered waste) (OECD iLibrary, 2022; PlasticsEurope, 2020). In 2015, the European Commission (EC) adopted a circular economy action plan (CEAP) with measures for Europe to transit towards a circular economy, promote sustainable economic growth, and increase global competitiveness (EC, 2015). In 2018, the CEAP was followed up with an action plan dedicated to plastics titled *A European Strategy for Plastics in a Circular Economy*, which had the aim of transforming the ways in which plastic products are designed, produced, used and recycled in the EU. In addition, the strategy recognizes innovation as a critical enabler of system transformation (EC, 2018).

Plastic lifetimes vary between different use sectors and product categories. Most packaging plastic becomes waste in the same year as it

* Corresponding author.
E-mail address: alla.toktarova@chalmers.se (A. Toktarova).

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is produced, while most construction plastic stays in use for decades (Geyer et al., 2017). To compensate for uneven plastic waste inflows and increasing demand for high-quality plastics, while decoupling plastics production from fossil resources, biomass and waste can be used as sources of carbon to produce plastic (Hasan et al., 2021; VELA, 2022). Biomass usage is an important part of climate mitigation strategies for many sectors, although the sustainably managed biomass resource is limited (Calvin et al., 2021).

Currently, waste in Europe is either disposed of in landfills or incinerated, in both cases with partial energy recovery (Eurostat, 2022). In northern and central Europe, waste is mainly incinerated with energy recovery in waste-to-energy plants and landfill disposal is limited or banned, whereas in southern and eastern Europe, the waste is mainly landfilled with partial biogas recovery (Aracil et al., 2017). The advantages of waste incineration include mass and volume reductions of 70% and 90%, respectively, energy recovery through heat and power generation, and a high-temperature sterilization effect (Kaza et al., 2018). Panepinto and Zanetti (2021) have defined indexes with the aim to choose an optimal method for handling of municipal waste, based on 16 existing plants (incineration and gasification/pyrolysis). They found that the ratio between emitted pollutant concentrations (nitrogen oxides and particulate matter) and the amount of treated waste is lower for existing waste incineration plants as compared to waste gasification and pyrolysis plants, while the ratio between CO_2 emissions and the amount of treated wastes are similar. However, the study lacks environmental indexes related to carbon recovery rate, which is an essential index in light of the transition into the circular economy.

In 2019, the EU excluded waste-to-energy incineration from the EU Taxonomy for sustainable activities (i.e., activities, investments and assets that can be considered to be supportive of the EU climate goals) (Vilella, 2019). Yet, waste incineration is currently excluded from the European Emissions Trading System (EU ETS). If waste incineration would be included in the EU ETS, the additional cost of incineration could act as an incentive for waste prevention and recycling, which would then become more competitive than incineration (Warringa, 2021).

Mechanical-thermal recycling is the main solution to the problems associated with the disposal of large-scale plastic wastes (Faraca and Astrup, 2019). However, when the sorting process cannot be used due to technical or economic limitations, the resulting mixed plastic waste consists of multiple types of polymers, which are largely immiscible. Most polymer blends exhibit weak mechanical performance (Maris et al., 2018). In addition, the secondary plastics produced by mechanical recycling have unpredictable rheologic properties, limiting their application in packaging and medical products (Al-Salem et al., 2019). The transition towards a circular economy requires a technology that treats any type of plastic waste (sorted or mixed) and produces plastics of the same quality as the original. Thermochemical recycling provides an alternative to conventional methods of plastic waste treatment (i.e., mechanical recycling and incineration). This process provides theoretically unlimited recycling of any plastic material (sorted or mixed), does not require extensive sorting practices, and operates under flexible conditions with low direct impacts on the environment (Soni et al., 2021; Thunman et al., 2019). However, thermochemical recycling is an energy-intensive process that requires electricity or fuels to operate.

Electrification of the chemical industry is gaining momentum, as seen in both research and industrial development projects (Hasan et al., 2021). The decline in investment costs for wind and solar generation technologies, as well as for battery storage has been faster than previously anticipated. Between 2010 and 2020, the global weighted-average total installed costs of solar PV, onshore and offshore wind fell by 85%, 31% and 32%, respectively (IRENA, 2021). Substantial cost decreases, competitiveness with new conventional electricity generation technologies, and low-carbon environmental impacts of electricity generation technologies based on Renewable Energy Sources (RES) have all made electrification a key pathway towards achieve transformation of industry (i.e., decarbonization and defossilization) (Lechtenböhmer et al., 2016; Wei and McMillan, 2019).

For chemical production processes, such as thermochemical recycling of plastics, two types of electrification are possible: direct use of electricity to provide heating and mechanical work in a chemical process; and indirect use of electricity to synthesize an alternative feedstock. Chen et al. (2021) have investigated the interactions that occur between electrified methanol production (which can be used as a building block for the production of plastics) and the electricity systems of the US and Germany, applying an optimization model. They have investigated the dual functionality of hydrogen storage as an energy storage system and as a material buffer for methanol production. They have shown that the cost-optimal configuration of the process is dependent upon the electricity system mix, i.e., that hydrogen storage capacity is 6.5-times larger in the wind-dominated region (Germany) than in the solar PV-dominated region (US). Thus, the size of the hydrogen storage correlates with wind and solar variations (i.e., variations up to several days for the wind-dominated region, and diurnal variations for the solar PV-dominated region).

The chemical companies BASF, SABIC and Linde have signed a joint agreement to develop and demonstrate solutions for direct electrification of steam cracking aimed at reducing CO_2 emissions from chemical production plants by 90% (BASF, 2022). The Dutch chemical company DOW aims to achieve net-zero emissions by Year (2050) through electrification of the steam crackers (DOW, 2022).

Previous studies of thermochemical recycling of plastics have focused on process modeling to investigate energy use and economic performance (Thunman et al., 2019), as well the impacts that its introduction will have on the global carbon flows (VELA, 2022). There are no published studies regarding the cost-optimal design and operation of the electrified process for plastics production, or on its impact on the electricity system. To fill this gap, we apply a linear cost-optimization model using the north European electricity system to analyze the impacts of an electrified chemical industry that is decoupled from fossil fuel extraction on investment decisions related to new electricity generation capacity and electricity trade. Furthermore, this work demonstrates how the spatial allocation of electricity-based thermochemical plastic recycling plants and their sizing are influenced by the electricity system.

1.1. Process description

Fig. 1 shows a schematic of the process for plastics production, which can be carried out via thermochemical plastic recycling (Thunman et al., 2019) and waste gasification (Arena et al., 2010; Kagayama et al., 1980; Panepinto et al., 2015). Table 1 gives an overview of the processes applied for the production of plastics in this work in terms of feedstock, process type, technology and process configuration.

The production of plastics can be divided into three main steps: olefins, plastic, and hydrogen production. Thermochemical recycling of plastic waste and waste gasification produce a raw syngas, which is further reformed into pure CO and H_2. The reformed syngas is used for methanol synthesis. The produced raw methanol is converted to olefins via the methanol-to-olefins process. Olefins are the building blocks for plastics production. The thermal cracking of the plastic waste ensures that a significant share of the plastic waste is directly recovered as olefins. The remaining CO and H_2 from the cracking process, as well as the CO_2emissions that arise from the process (encompassing the flue gas from the combustor of the cracker, the CO_2 separated from the cracker gas in the cleaning section, and the CO_2 produced in chemical factories) can be captured and converted to olefins through a synthesis process. Alternatively, the CO_2 can be captured and stored. CO_2 stream utilization for olefin synthesis requires balancing the hydrogen content of the syngas. Hydrogen is, in this case, produced via electrolysis. The oxygen, which is another product of the electrolysis, is used to generate a CO_2-rich stream from the combustion side of the cracker.

The temporal distribution of the electricity consumption of the

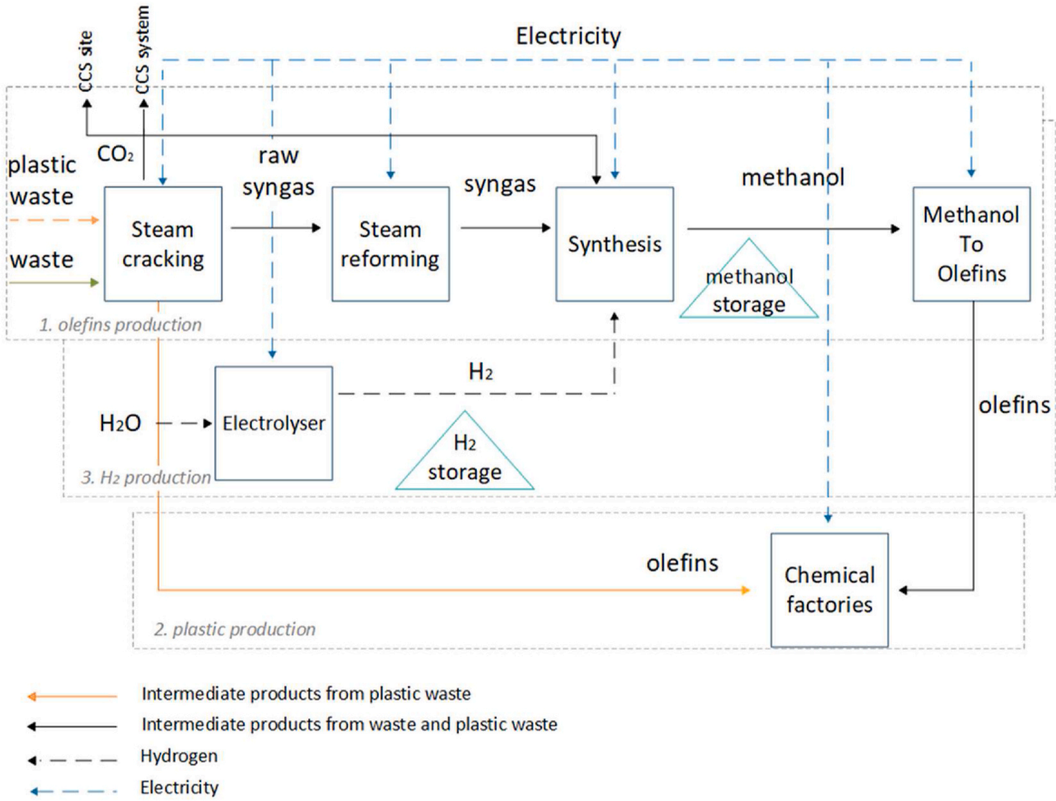

Fig. 1. Schematic of the plastics production process using thermochemical plastic recycling and waste gasification.

Table 1
Overview of the configurations for plastics production processes applied in this study.

	Route 1	Route 2
Feedstock	Plastic waste	Waste
Process	Thermochemical recycling	Gasification
Technology	Steam cracker (Fluidized bed reactor)	Steam cracker (Fluidized bed reactor)
Configuration	Fully electrified	Fully electrified

process can be made flexible through the storage of hydrogen and methanol. Methanol can be stored and exported for use as a base chemical at external production sites. In this work, it is assumed that the heat for the cracker is provided by electric heating, which is delivered through electrical coils installed in the bed material loop before the combustor (Pissot et al., 2020).

The electrolyzer has a high operational flexibility, i.e., it can be stopped and started relatively rapidly and at low cost. The steam cracker, steam reformer, and the synthesis and methanol-to-olefins processes have limited flexibility, i.e., they have to operate continuously without stops. For the steam cracker, the steam reformer and the methanol-to-olefins process, the output can fluctuate within the operational range of 100%–50% of full capacity. The operation of the synthesis process can be reduced to 25% of full capacity (Larsson et al., 2018).

2. Method description

In this work, we develop and implement a plastics production process module in a cost-minimizing, electricity system investment model, called eNODE, to investigate the impacts of thermochemical plastic recycling on investments in and operation of the electricity system. In addition, we examine the impacts of the electricity system on the design and location of plastics recycling units. A full mathematical description of the original electricity system investment model is given in a recent publication (Walter et al., 2022), and Figure A1 in Appendix A gives an overview of the model. The inclusion of the plastics production process module provides descriptions of: (i) the decisions made regarding investments in plastics production capacities and storage technologies (H_2 storage and methanol storage), as outlined in Fig. 1; (ii) the locations of plastics production capacities and storage units; (iii) the cost of plastics; and (iv) the CO_2 utilization modes. Details of the objective function of the model and the plastics production process module are provided in Appendix A.

2.1. Electricity system investment model

The eNODE model with the new plastics production module minimizes the investments and running costs of the electricity system of northern Europe, while meeting the demands for electricity and plastic. Thus, the objective functions can be written as:

$$\begin{aligned} min : C^{tot} = & \sum_{r\in R}\sum_{p\in P\setminus P^{transm}} i_{p,r}\left(C_p^{inv} + C_p^{O\&M,fix}\right) + \sum_{t\in T} C_{p,t}^{cycl} + C_{p,t}^{run} g_{p,t,r} \\ & + \sum_{r_2\in R\setminus r}\sum_{p\in P^{transm}} C_{p,r,r_2}^{inv} i_{p,r,r_2} + \sum_{p\in P^{plastic}\cup P^{transm}}\sum_{t\in T} C_{r,r_2}^{transp} e_{p,t,r,r_2}^{pos} \\ & + \sum_{p\in P^{plastic}}\sum_{t\in T} C^{st} b_{p,t}^{CCS} \end{aligned} \quad (1)$$

where P is the set of all technologies, T is the set of time-steps, and R is the set of the regions. The annualized investment costs, the fixed operational and maintenance costs, the running costs and the cycling cost per technology p at time-step t are denoted C_p^{inv}, $C_p^{O\&M,fix}$, $C_{p,t}^{run}$ and $C_{p,t}^{cycl}$, respectively. The variable $i_{p,r}$ is the capacity investment per technology p that is installed in region r, and $g_{p,t,r}$ is the generation of electricity and production of commodities (i.e., methanol and plastics) per time-step t and region r, respectively. For the product trade that is transmitted/

produced by technologies P^{transm} (the subset of P for transmission lines) and $P^{plastic}$ (the subset of P for plastics production units) between regions r and r_2 at per time-step t, the costs C^{transp}_{r,r_2} are considered. The CO_2 emissions $b_{p,t}$ from technology $P^{plastic}$ at time-step t are captured and stored at cost C^{st}. The electricity demand must be satisfied for each time-step t and region r. The electricity balance that matches the supply to demand while considering electricity trade between the regions is written as:

$$\sum_{p\in P^{el}} g_{p,t,r} + \sum_{p\in P^{STR}\setminus P^{methanol}\cup P^{H_2}} z^{dis}_{p,t,r} \geq D_{r,t} + \sum_{p\in P^{plastic}} g_{p,t,r} f_p + \sum_{p\in P^{STR}\setminus P^{methanol}\cup P^{H_2}} z^{ch}_{p,t,r} + \sum_{r_2\in R\setminus r} \sum_{p\in P^{transm}} e_{p,t,r,r_2}, \quad \forall t \in T, \forall r \in R \tag{2}$$

where P^{el} is the subset of P for all electricity generation technologies. The demand for electricity, $D_{r,t}$, is given per region r and time-step t, the electricity generation $g_{p,t,r}$ per technology p, region r and time-step t, and e_{p,t,r,r_2} is the electricity trade from region r to region r_2 per time-step t. The charging and discharging of electricity storage technology P^{STR} at time-step t in region r are written as $z^{ch}_{p,t,r}$ and $z^{dis}_{p,t,r}$, respectively. The parameter $f_{p,r}$ describes the electricity demand from the plastics

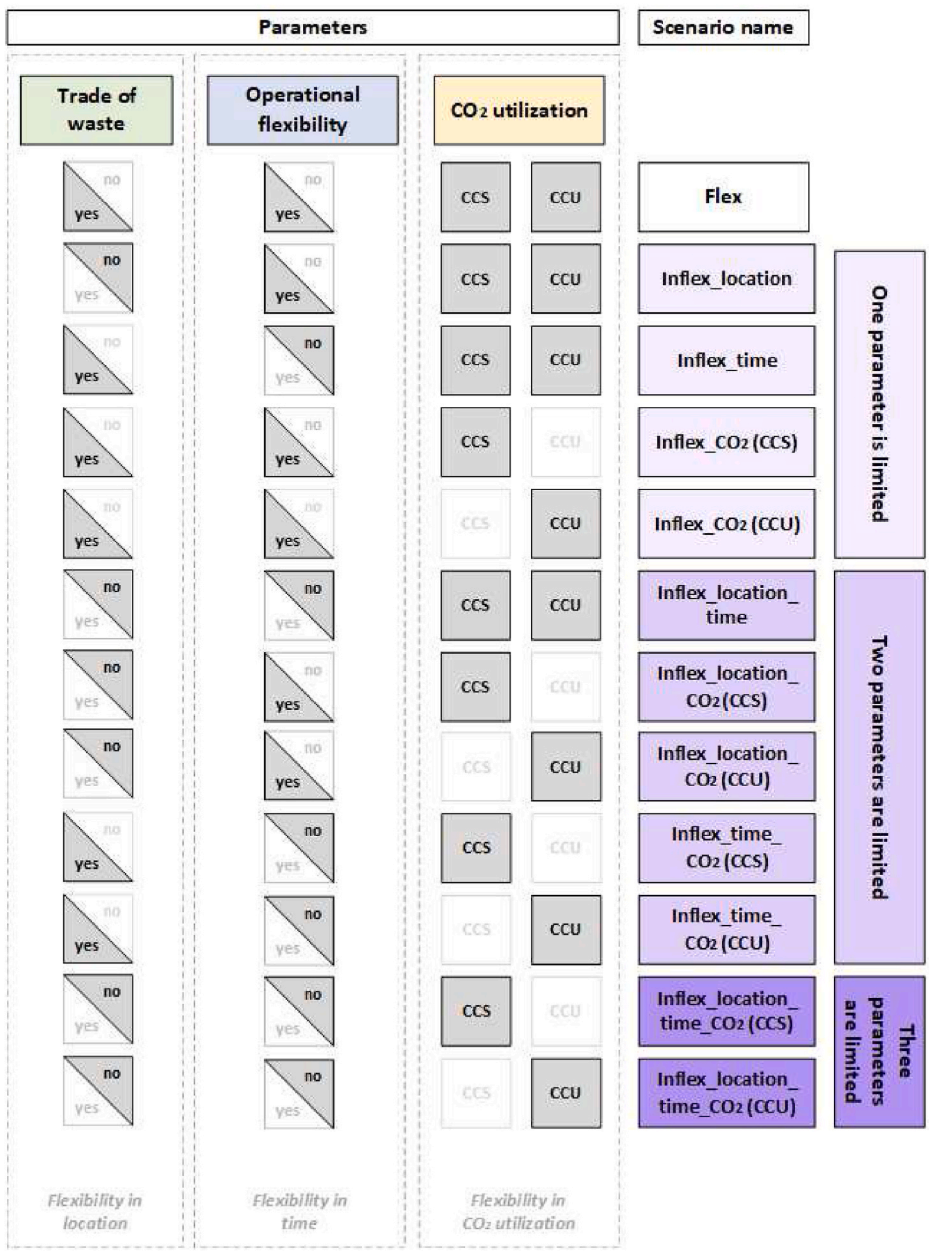

Fig. 2. Schematic overview of the parameters that define the investigated scenarios.

production technology $P^{plastic}$.

The electricity generation technologies considered in the model, including storage and transmission technologies, and their main properties are listed in Appendix B, Table B1. The model accounts for the economic and technical properties of the technologies, including start-up cost, start-up time and minimum load level of thermal generation. In terms of energy storage technologies, investments in lithium-ion batteries and H_2 storage are possible in all the regions considered. In this work, northern Europe encompasses the following countries: Belgium, Denmark, Estonia, Germany, Ireland, Latvia, Lithuania, the Netherlands, Norway, Poland, Sweden, and the UK. These countries are subdivided into 12 regions based on the current bottlenecks in transmission grid. Within the 12 regions considered, it is assumed that electricity can be transmitted without internal congestion. Trade between regions is limited by the transmission capacity with the exiting grid capacity as a starting point, and the possibility to invest in additional capacity. Existing hydropower is included in the model and no new hydropower investments are possible. For other types of electricity generation and storage, the model takes a greenfield approach, which implies that capacity is only available if a new investment is made. The greenfield perspective provides long-term benchmarks for plastics production in an optimized future electricity system, as well as qualitative insights into the interdependencies of plastics production and the electricity system. The locations and capacities of the existing chemical factories are used in the model (Appendix B; Table B2), while the capacity and location of other parts of the plastics recycling process are decision variables in the model. The modeled year represents a future year with net-zero CO_2 emissions from electricity generation and plastics production (i.e., around Year, 2050 if complying with the Paris Agreement). The net-zero CO_2 emissions constraint means that all emissions in the modeled system should be either stored and captured or covered by negative-emissions technologies (BECCS, bioenergy with carbon capture and storage). A time-period clustering technique that retains the chronology throughout the year is applied (Pineda and Morales, 2018).

2.2. Assumptions and scenarios

Fig. 2 gives an overview of the parameters that define the different scenarios applied in the model analysis. Three parameters (operational flexibility, trade of waste, and CO_2 utilization) represent the flexibility options (flexibility in time and location and flexibility in CO_2 utilization) that can be applied (the square under the parameter name indicates "yes") or limited (the square under the parameter name indicates "no") in the modeled thermochemical recycling process for plastics and waste gasification process.

The flexibility in time is defined by operational flexibility, i.e., the ability of the plastics production unit to vary the output within the load ranges. In the absence of flexibility in time, the capacity utilization rate is 100%, i.e., there are no investments in overcapacity and storage. The flexibility in location is defined by the ability to export commodities (waste, plastic waste, methanol and plastics). With flexibility in location, it is possible to allocate plastics production units to regions without existing plastics production. The flexibility in CO_2 utilization is used to describe the ability of plastics production units to vary the CO_2 utilization modes, i.e., CO_2 usage for plastics production and CCS (two squares under the parameter CO_2 utilization marked in gray). If only one square under the parameter 'CO_2 utilization' is marked in gray this means that only CCU or CCS can be used to utilize CO_2 emissions if available. The scenarios are presented in order of decreasing flexibility, i.e., starting with the fully flexible process, followed by scenarios with one limited flexibility option, then two flexibility options and, finally, the inflexible scenarios. The scenario names indicate type of inflexibility in the applied scenario. In the case of limitation as to CO_2 utilization, two naming options are applied, i.e., CO_2(CCS) and CO_2(CCU).

Feedstock. In all the investigated scenarios, a waste mix and plastic waste are used as feedstocks to produce plastic (see Table B3 in Appendix B). The collected post-consumer packaging plastic waste per region is used as the plastics waste in this study. The usage of plastic waste packaging allows maximization of the direct recovery of olefins in the thermochemical recycling process. It is assumed that waste that is currently being incinerated is available for waste gasification to produce plastics, which is in line with the CEAP adopted in Year (2020) (EU, 2020). The current waste-to-energy capacity in the EU is about 90 Mt (Stengler, 2019).

Transport costs. Distance-dependent transport costs for commodities are assumed, i.e., the transport distance between regions and the amount of transported commodity are considered. The transportation costs for plastic waste, methanol and plastic are taken from a previous study (van der Meulen et al., 2020). For plastic waste and waste transportation, the costs of dry bulk commodities are assumed, and for methanol, the costs of liquid bulk commodities are assumed.

Demand driver. The current (Year, 2020) demands for plastics in the investigated regions are applied as the regional plastic demand (see Table B3 in Appendix B).

Commodity export. The export of plastic waste, methanol and plastics is allowed in all the investigated scenarios. As for the export of waste, this variable varies between the scenarios investigated. In 2021, the EC adopted a proposal for a new regulation on waste shipments. This regulation aims to establish stricter rules for waste shipments for landfilling or incineration, and to make it easier to transport waste for recycling or reuse within the EU (EC, 2021). In the scenarios with limited flexibility regarding location, waste shipments are not allowed, and waste can be utilized only where the current waste-to-energy plants are located, to take advantage of the existing infrastructure and logistic. Thus, in the model, the current waste incineration facilities are assumed to be transformed into gasification plants. Due to the geographic scope limitation of this study, trade in commodities takes place only within northern Europe.

Operational flexibility. The scenarios include two representations of the operational flexibility:

1. Flexible operation. Electrolysis is assumed to have high operational flexibility levels, i.e., it can be stopped and started without efficiency losses and additional costs linked to starting up (FCH, 2019). The steam cracker, steam reformer, and synthesis and methanol-to-olefins processes have limited flexibility, i.e., they operate continuously without stops and their outputs can fluctuate within the operational range of 100%–50% of full capacity (for synthesis, to 25% of full capacity).
2. Inflexible operation. The operational range of 100%–94% of capacity (due to computational reasons) is assumed for all the plastics production capacities (the steam cracker, steam reformer, synthesis, electrolyzer and methanol-to-olefins process). The operation of plastics production within this range gives a capacity utilization rate of close to 100%.

CO_2 utilization. The CO_2 emissions arising from the process can be utilized in three different ways:

1. Optimized CO_2 stream utilization. The model optimizes the CO_2 utilization mode, i.e., flexible operation ranging between CO_2 usage for plastics production and CCS.
2. 100% circularity (CCU). All CO_2 emissions released are utilized to produce plastics, i.e., strict carbon capture and utilization mode.
3. 100% CCS. All CO_2 emissions released from feedstock processing are captured and stored.

Regions with good conditions for wind and solar power generation can provide low-cost electricity to meet the new electricity demands. In the model, conditions for wind and solar generation are defined by the hourly generation profiles and available land for solar and wind power. In this study, favorable conditions for wind and solar PV generation are referred to in terms of availability of low-cost electricity generation. The capacity utilization rate indicates how much of the plastics production capacity is being utilized, i.e., actual output divided by potential output. When the capacity utilization rate is <100%, it means the plant is not using all of its installed capacity at all times, i.e., there is an investment in overcapacity to achieve flexibility. In this study, the percentage of carbon in the feedstock provided to the cracker that ends up in the final products is referred to as 'the rate of carbon recovery'.

2.3. Sensitivity analysis

Nuclear capacity in Germany. The model applied in this study is greenfield, and the existing electricity generation capacity as well as current decisions regarding changes to the electricity system are omitted. Nonetheless, the transmission lines, hydropower power, and nuclear power in Finland (commercial operation of the new Olkiluoto 1.6 GW reactor is planned start by July 2022) are taken into consideration in the model. Germany is planning to phase out nuclear power reactors (4 GWh) at the end of Year (2022), in line with the complete nuclear phase-out plan drawn up in Year (2011). Thus, a sensitivity analysis was conducted to investigate the impact of not allowing for investments in nuclear power in Germany (i.e., regions DE_S and DE_N).

H_2 storage costs. To account for uncertainties related to technology costs, a sensitivity analysis was conducted that involved changing the cost of hydrogen storage (investment costs were reduced and increased by 50% and 90% relative to the costs applied in the model, as given in Appendix B; Table B1).

Additional methanol production. The total amount of carbon available in the forms of plastic waste and waste is larger than the amount of carbon needed to satisfy the demand for plastics. To investigate a situation in which all of the carbon in plastic waste and waste is utilized, a methanol demand was introduced to the model in addition to the plastics demand. The allocation of methanol production is implemented as a decision variable, i.e., production is placed where it is most cost-efficient from a system perspective.

The sensitivity analysis was applied to the *Inflex_location* scenario (scenario with limited flexibility in regard to location, i.e., trade of waste is not allowed). This scenario was chosen because it limits the possibility to compensate for restrictions regarding nuclear power investments, high cost of hydrogen storage, and an extensive hydrogen demand by moving parts of the plastics production process geographically. The consequences of the aspects investigated in the sensitivity analysis should, thus, be more severe in the *Inflex_location* scenario than in the *Flex* scenario.

3. Results

The results are presented in the following five subsections. The first subsection describes the plastics production costs and total system costs for the investigated scenarios. The second subsection presents how electrified production of plastics influences investments in electricity generation capacities and electricity trade between investigated regions. The third subsection illustrates the plastics production units' locations and sizes in the investigated scenarios. The fourth subsection gives the dispatch of the CO_2 utilization for plastics production and CCS. Finally, the fifth subsection presents the results of the sensitivity analysis, i.e., the impact of adding a demand for methanol, the impacts of a cost increase and decrease of hydrogen storage, and the impact of a limitation being imposed on nuclear power investments in Germany.

3.1. Plastics production cost and total system cost

Fig. 3 presents the breakdown of the plastics production cost per tonne of plastic for the twelve scenarios modeled. The cost is divided into the feedstock costs (i.e., plastic waste and waste), cost to capture and store CO_2, the annualized investment cost, the fixed operation and maintenance costs (O&M) costs, the cost of electricity, and the transportation costs. The cost of electricity as experienced by the producer of the plastics is here taken as the consumption-weighted electricity price, where the marginal cost of electricity is taken as a proxy for the electricity price and is a result of the modeling, i.e., the marginal value from Eq. (2). The marginal value reflects the cost to supply one additional unit of electricity to the energy system.

The total system cost, which includes the investment and running costs for the electricity system and the plastics production industry [value from Eq. (1)], for the investigated scenarios (see *Assumptions and scenarios*) and for the scenario without electrified plastics production, is shown in Fig. 4. The values on top of the bars indicate the total system

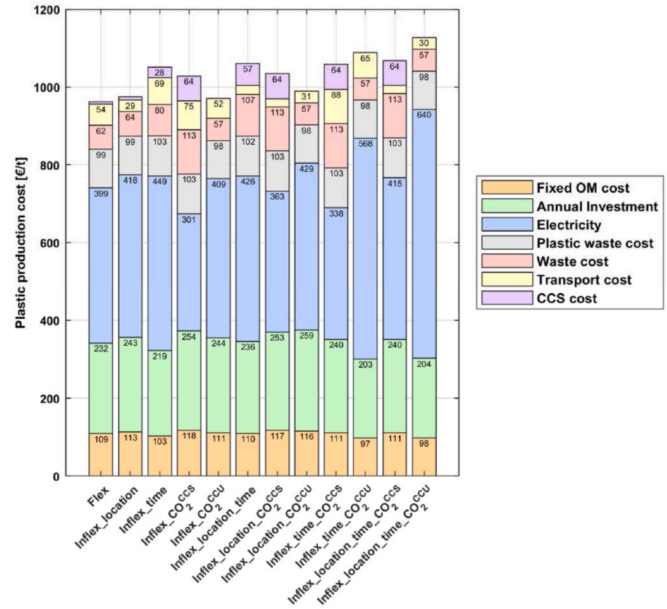

Fig. 3. Breakdown of the modeled cost of plastics production for the twelve modeled scenarios into feedstock costs, cost of capture and storage of CO_2, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs.

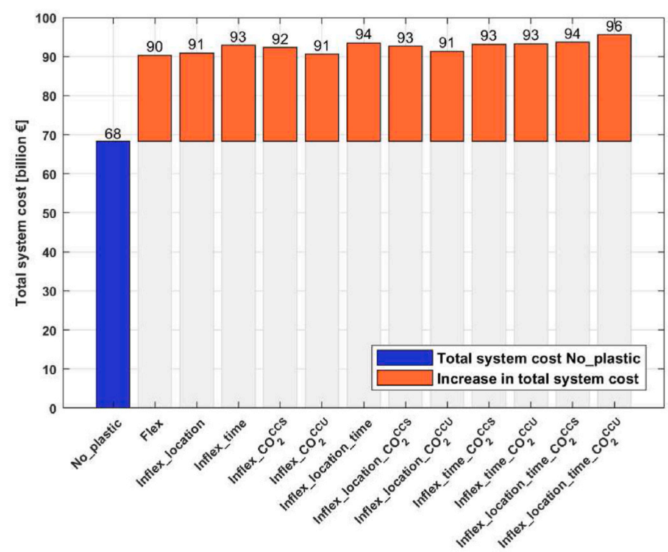

Fig. 4. The total system costs (in billions of Euro) for the investigated scenarios and for the electricity system without electrified production of plastics.

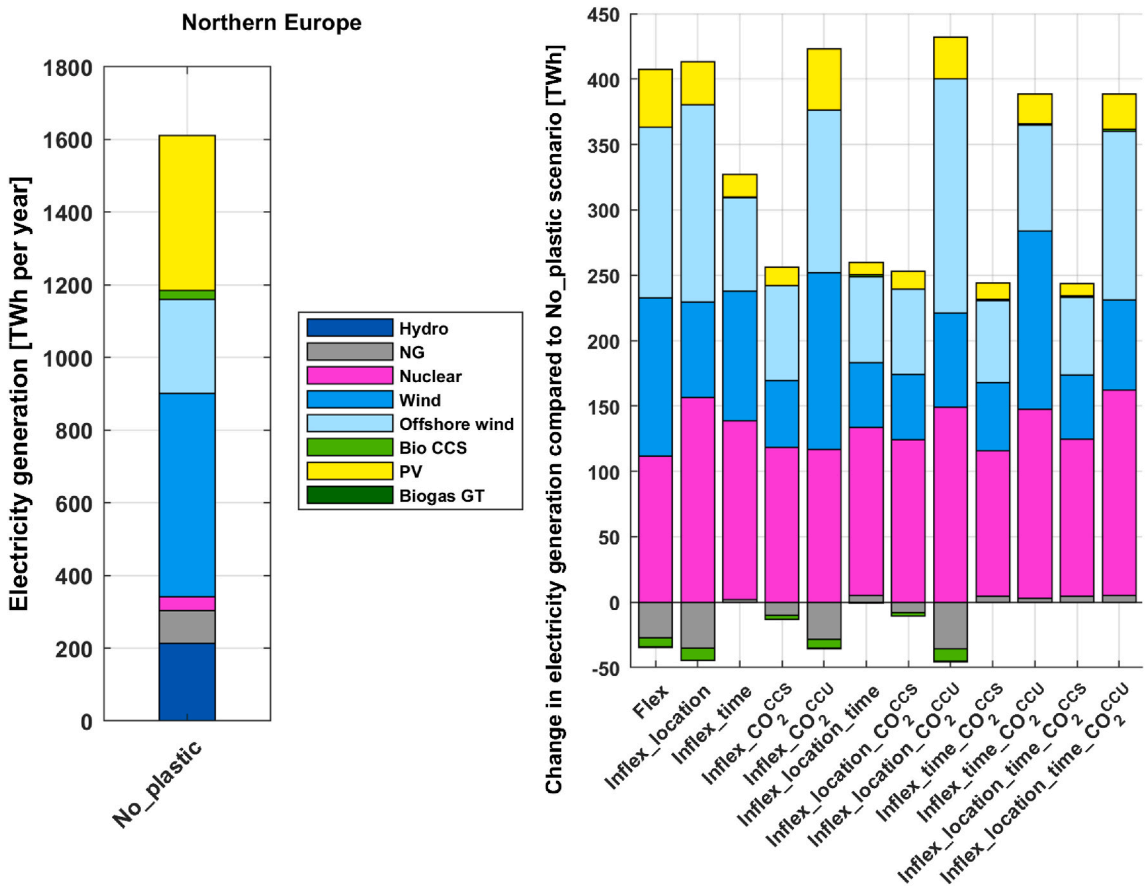

Fig. 5. Total annual electricity generation (in TWh) for the scenario without electrified plastics production (left-hand panel) and the differences (in TWh) in electricity generation between an electricity system without electrified plastics production and the scenarios with electrified plastics production (right-hand panel) for northern Europe. NG, natural gas; GT, gas turbine; Bio, biomass; CCS, carbon capture and storage; PV, photovoltaic.

cost in billions of Euro. The orange segments for the scenarios with electrified production of plastics represent increases in total system cost compared to the scenario without plastics production (€68 billion).

The modeling results given in Fig. 3 yield a plastics production cost in the range of 960–1130 €/t for the investigated scenarios. The total system cost increase varies in the range of 22–27 billion Euro for the investigated scenarios (Fig. 4). The increases in total cost for all the scenarios investigated originate from both the electricity system (investments in and operation of new electricity generation technologies; Fig. 5) and the plastics industry (investments in and operation of plastics production units; Figs. 7 and 8). As can be seen, the cost of electricity is the largest cost in all the scenarios, followed by the annualized investment cost. The lowest cost for plastics production (€960 per tonne) and the total cost (€90 billion) are obtained for the *Flex* scenario with full flexibility, i.e., flexibility of time and location, and flexibility of CO_2 utilization (Figs. 3 and 4). The *Flex* scenario has the highest carbon recovery rate and the lowest CCS cost among the scenarios with flexible CO_2 utilization.

Among the investigated scenarios in which only one parameter is limited (see Fig. 2), the limitation with regard to flexibility in time has the highest impact, i.e., the plastics production cost in *Inflex_time* scenario increases by 9% as compared to the *Flex* scenario. The prominent increase in production costs is due to an increase in electricity costs (13% increase compared to the *Flex* scenario), which is a consequence of the limitation regarding the flexibility in time, i.e., the electricity consumption of the plastics production units cannot be shifted in time. In the *Inflex_time* scenario, there is also an increase in the CCS cost compared to the *Flex* scenario, which means that flexibility in CO_2 utilization compensates for the limitation of the flexibility in time.

The *Inflex_CO$_2$(CCU)* scenario shows the lowest cost increase (1%) compared to the *Flex* scenario, among all the investigated scenarios with limited flexibility. The limitation regarding the flexibility of CO_2 utilization leads to a decrease in the plastics production capacity utilization rate, i.e., increase the value of the flexibility in time.

In the *Inflex_CO$_2$(CCS)* scenario, both the transportation cost and investment cost increase equally, as compared to the corresponding costs in the *Flex* scenario. The high investment costs (240–254 €/t) in the scenarios with limited flexibility regarding CO_2 utilization (in this case, CCS) are explained by a larger cracker capacity than in the scenarios without CO_2 utilization limitations, since CO_2 released from the processing of feedstock is captured and stored instead of being reused in the plastics production process. Thus, more feedstocks need to be processed to recover the required amount of carbon. In addition, overinvestments occur to avoid high electricity price hours for the plastics production units.

The main increase in plastics production cost when the flexibility with regard to location is limited (the *Inflex_location* scenario) comes from investments costs, i.e., a 5% increase as compared to the *Flex* scenario. The overinvestments in plastics production capacity are made to avoid electricity consumption during high-net-load events, i.e., flexibility in time compensates for the limited flexibility in location.

The limitations of the two flexibility options, as applied in the *Inflex_location_time*, *Inflex_location_CO$_2$(CCS)*, *Inflex_location_CO$_2$(CCU)*, *Inflex_time_CO$_2$(CCS)* and *Inflex_time_CO$_2$(CCU)* scenarios, stimulate investments to achieve flexibility via the available flexibility option. For the *Inflex_location_CO$_2$(CCS)* and *Inflex_location_CO$_2$(CCU)* scenarios, limitations of the flexibility regarding CO_2 utilization and location stimulate investments to achieve flexibility in time, as indicated by high

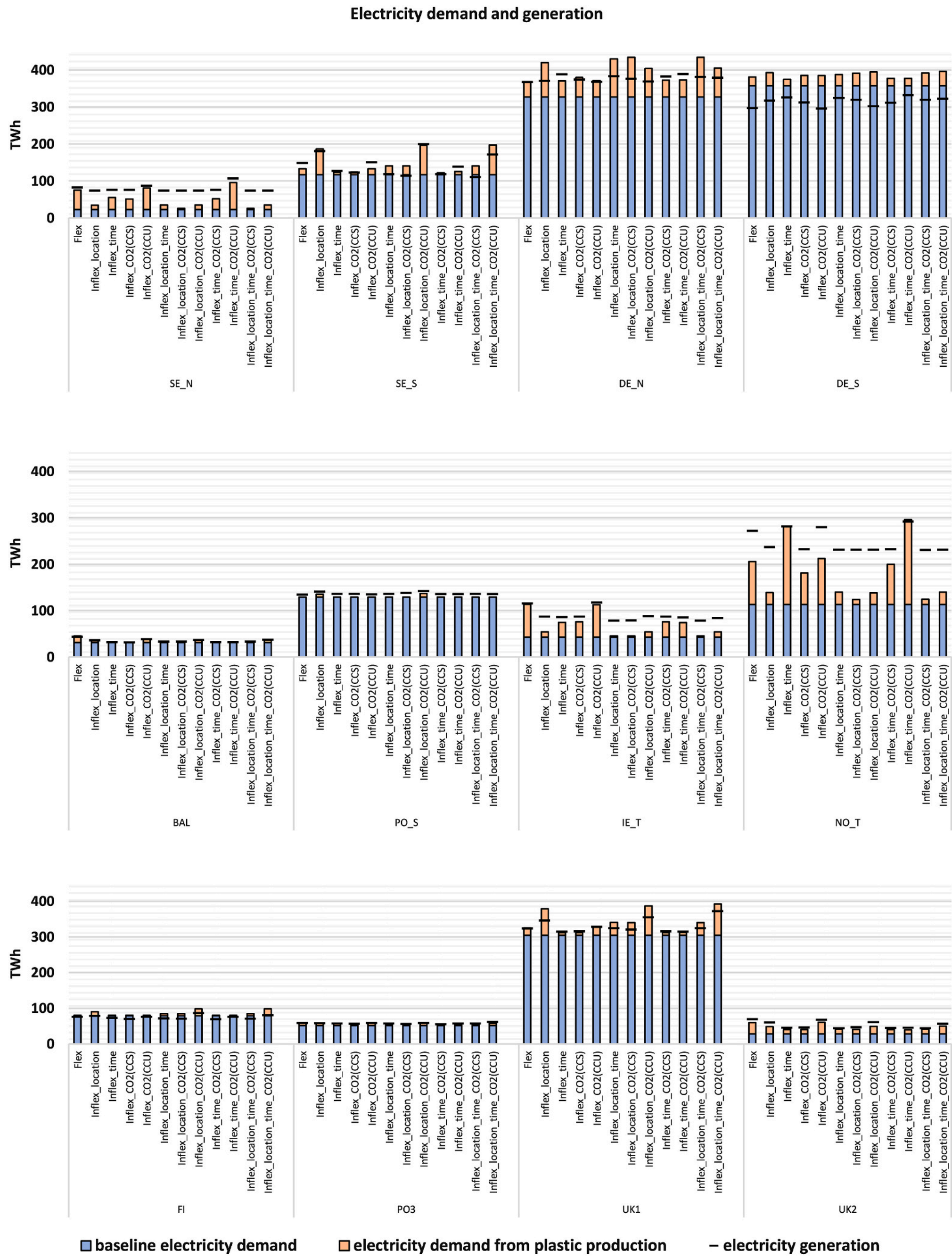

Fig. 6. Total annual electricity generation, baseline electricity demand and electricity demand from plastics production (in TWh) for the scenarios investigated (see *Investigated scenarios*) for each modeled region.

annualized investment costs, i.e., 253 €/t and 259 €/t respectively. The *Inflex_location_CO$_2$(CCU)* scenario has the highest investment cost (259 €/t) among the scenarios investigated due to overinvestments in electrolyzer capacity, as well as in plastics production capacity, to avoid hydrogen production during high electricity price hours. Despite these overinvestments, the *Inflex_location_CO$_2$(CCU)* scenario gives the second-highest electricity costs among the scenarios (568 €/t), which is explained by a high demand for hydrogen to utilize all the CO_2 emissions released from processing the feedstock in this scenario.

The cost of transportation of commodities (plastic waste, waste methanol and plastic) are four-fold higher for *Inflex_time_CO$_2$(CCS)* and three-fold higher for *Inflex_time_CO$_2$(CCU)* as compared to the lowest cost of transportation (21 €/t) for the *Inflex_location_time_CO$_2$(CCS)* scenario. These results indicate that when CO_2 utilization is predetermined and there is no flexibility in time the flexibility with regard to location is of high value. The limitation of the flexibility of both time and location in the *Inflex_location_time* scenario increases the use of the CO_2 utilization flexibility, with the highest CCS cost (57 €/t) being noted for scenarios with flexible CO_2 utilization. However, this also means that this scenario results in the lowest carbon recovery rate.

With no flexibility in time, a high CO_2 utilization rate results in a high cost for electricity, with a high total production cost as a consequence. The costs for plastics are 1127 €/t for the *Inflex_location_time_CO$_2$(CCU)* scenario and 1088 €/t for the *Inflex_time_CO$_2$(CCU)* scenario. The limitation of all the flexibility options but with a low CO_2 utilization rate, as applied in *Inflex_location_time_CO$_2$(CCS)*, gives the third-highest plastics production cost of 1068 €/t.

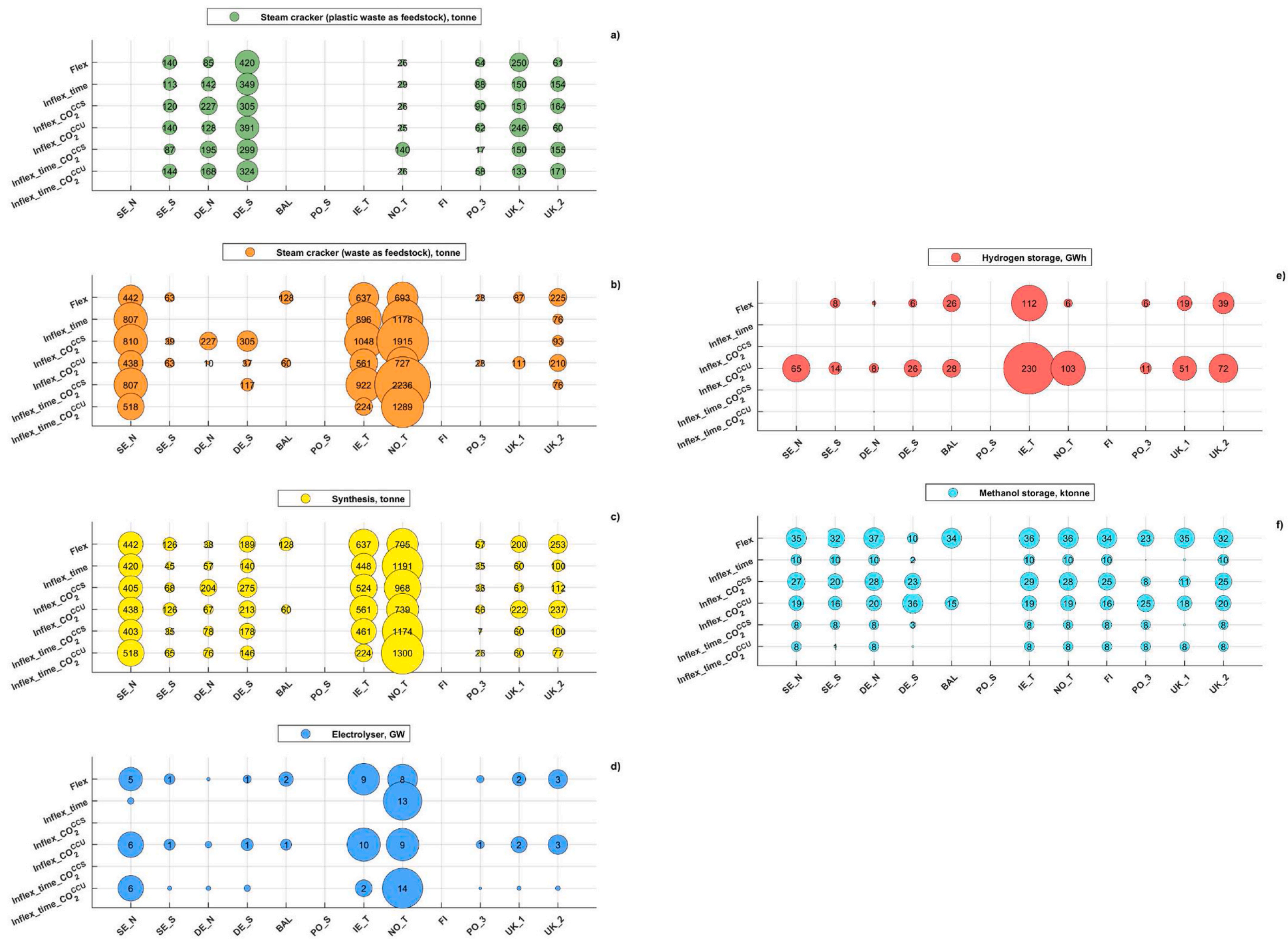

Fig. 7. The modeling results for the scenarios without limitation in flexibility in location (*Flex, Inflex_time*, *Inflex_CO$_2$(CCS)*, *Inflex_CO$_2$(CCU)*, *Inflex_time_CO$_2$(CCS), Inflex_time_CO$_2$(CCU)*). The regional allocations of the plastics production capacities are given in terms of the stream crackers in ktonne (a and b), synthesis plant in ktonne (c), electrolyzer in GW (d), hydrogen storage in GWh (e) and methanol storage in ktonne (f).

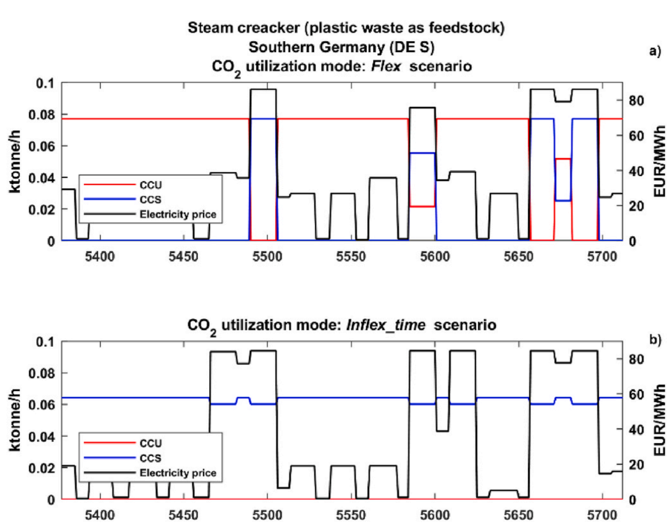

Fig. 8. Electricity price profiles (€/MWh) and CO_2 utilization levels (ktonne) (i.e., CCS and CCU) for steam crackers based on plastic waste for southern Germany (DE_S) for the *Flex* (a) and *Inflex_time* (b) scenarios for 2 weeks in September. CCS, carbon capture and storage; CCU, carbon capture and utilization.

3.2. *Electricity system compositions to satisfy the electricity demand for plastics production*

3.2.1. *Investments in electricity generation technologies*

Fig. 5 presents the electricity production levels of northern Europe without electrified production of plastics (left-hand panels), and shows how this production pattern changes for the different scenarios (see Fig. 2) with electrified production (right-hand panels) for the net-zero emissions system.

As illustrated in Fig. 5, wind power and solar power dominate the supply-side of the electricity system with net-zero emissions in northern Europe. To meet the demand for plastics, the total annual level of electricity generation increases in the range of 240–400 TWh for all the investigated scenarios. The additional electricity demand for plastics production is mainly covered by production from wind and nuclear power, while it reduces the production of electricity from natural gas-based generation technologies. The reduction of electricity generation from NG-based technologies leads to reduced production from the bio-CCS technology, which provides negative emissions to compensate for the fossil-related emissions. With limited flexibility in time, as applied in the *Inflex_time, Inflex_location_time, Inflex_time_CO$_2$(CCU)*, *Inflex_location_time_CO$_2$(CCS)*, and *Inflex_location_time_CO$_2$(CCU)* scenarios, the decrease in flexible thermal generation based on biogas and natural gas is small. The limitation as to CO_2 utilization flexibility when all the CO_2 emissions released are used to produce plastic, as applied in the *Inflex*

_CO_2(CCU), *Inflex_location_CO_2(CCU)*, *Inflex_time_CO_2(CCU)* and *Inflex_location_time_CO_2(CCU)* scenarios, provides the largest increase (24%) in electricity generation compared to an electricity system without electrified plastics production (*No_plastic* scenario). The *Flex* scenario, in which a high share of CO_2 utilization is cost-efficient, shows similar results. For scenarios with a high level of CO_2 utilization and flexibility in time, a large part of the electricity demand for plastics production is supplied by wind and solar power. When all the CO_2 emissions released are captured and stored [*Inflex _CO_2(CCS)*, *Inflex_location_CO_2(CCS)*, *Inflex_time_CO_2(CCS)* and *Inflex_location_time_CO_2 (CCS)*], the increase (15%) in electricity generation relative to the *No_plastic* scenario is the lowest among all the scenarios investigated. For the scenarios with inflexible location of plastics production, nuclear power plays an important role in supplying the electricity demand.

3.2.2. Net export of electricity

Fig. 6 presents the modeled results for electricity generation and electricity demand, i.e., baseline electricity demand, which is taken from ENTSO-E (ENTSO-E, 2017), and for the electricity demand from plastics production, for all scenarios and regions investigated. The difference between the electricity generation level and electricity demand indicates the net export of electricity for the regions investigated.

Fig. 6 shows that the availability of large volumes of waste, as in southern and northern Germany, England and southern Sweden, and favorable conditions for wind power generation, as in Ireland, Scotland, northern Sweden and Norway, determine the allocation of plastics production units. The flexibility of the electrified plastics production process affects the magnitude of the electricity demand, as well as trade between regions for the scenarios investigated.

In regions with availability of large volumes of waste, such as southern Sweden, northern Germany and England, the limitation regarding the flexibility of location (no export of waste), as applied in the *Inflex_location, Inflex_location_time, Inflex_location_CO_2(CCS)*, *Inflex_location_CO_2(CCU)*, *Inflex_location_time_CO_2(CCS)*, and *Inflex_location_time_CO_2(CCU)* scenarios, leads to an increase in electricity import, since plastics production units cannot be allocated to the regions with more-favorable conditions for low-cost electricity. In regions with favorable conditions for wind power generation, such as Ireland, Scotland and northern Sweden, electricity demand for plastics production is met by increased local electricity generation, and these regions remain electricity exporters regardless of the flexibility limitations of the plastics production process applied in the investigated scenarios. However, for the scenarios with full flexibility (the *Flex*) and with the limitation of CO_2 utilization flexibility (*Inflex_CCU*), notable reductions in the levels of export of electricity are observed for northern Sweden and Ireland. In these scenarios, the export of electricity decreases, since the plastics production units located in northern Sweden and Ireland produce according to electricity price variations and utilize all hours with low electricity prices. A similar pattern, i.e., reduced export of electricity, is seen for scenarios with limited flexibility in time, i.e., the *Inflex_time* and *Inflex_time_CO_2(CCU)* scenarios, in Norway. The limitation regarding time flexibility for the plastics production process leads to the increased production of plastics in regions with a low average electricity cost, such as Norway.

3.3. Sizes and locations of plastics production plants

Fig. 7 shows the modeling results for the locations and sizes of the plastics production units [stream crackers (a and b), synthesis plant (c), electrolyzer (d), hydrogen storage (e) and methanol storage (f)] (see *Process description* section) for scenarios without limitation as to flexibility of location [*Flex, Inflex_time*, *Inflex_CO_2(CCS)*, *Inflex_CO_2(CCU)*, *Inflex_time_CO_2(CCS), Inflex_time_CO_2(CCU)*]. The modeling results for scenarios with limited flexibility regarding location, such as the *Inflex_location, Inflex_location_time, Inflex_location_CO_2(CCS), Inflex_location_CO_2(CCU)*, *Inflex_location_time_CO_2(CCS)*, and *Inflex_location_time_CO_2(CCU)* scenarios, are given in Appendix D, Figure D2. All the capacities of the plastics production units, except for those of the electrolyzer and hydrogen storage, are given in ktonne (Fig. 7, a–c, f). The electrolyzer capacity is presented in GW (Fig. 7d) and the H_2 storage capacity in GWh (Fig. 7e).

In all the investigated scenarios, the steam cracker capacity with plastic waste as feedstock is allocated to those regions with existing chemical factories (cf. Tables B2 and B3 in Appendix B). Since the olefins that are stream-produced from cracking plastic waste are costly to store and transport, they are supplied directly to the chemical plant to produce plastics. With flexibility regarding location (i.e., export of waste is allowed), as applied in *Flex, Inflex_time*, *Inflex_CO_2(CCS)*, *Inflex_CO_2(CCU)*, *Inflex_time_CO_2(CCS)* and *Inflex_time_CO_2(CCU)* scenarios, the availability of low-cost electricity generation from wind and hydro is a factor that defines the location of the steam cracker, which uses waste as a feedstock (Fig. 7b). Fig. 7b shows that limitation of the flexibility in time [*Inflex_time*, *Inflex_time_CO_2(CCS)* and *Inflex_time_CO_2(CCU)*] increases clustering of the steam cracker capacity with waste around regions with strong availability of low-cost electricity, such as Norway (NO_T), northern Sweden (SE_N), Ireland (IE_T), and Scotland (UK_2).

Fig. 7c and d show that the synthesis plant and electrolyzer capacity follow the regional allocation of the crackers (Fig. 7a and b). Regions with strong availability of low-cost electricity generation [e.g., Ireland (IE_T), Scotland (UK_2), Norway (NO_T) and northern Sweden (SE_N)] have the largest capacities of these units (synthesis plant and electrolyzer capacities) among the investigated regions for scenarios with flexibility of location. In the scenarios with limited flexibility of CO_2 utilization, when all the CO_2 emissions from the process are captured and stored [*Inflex_CO_2(CCS)*, *Inflex_time_CO_2(CCS)* *Inflex_location_CO_2(CCS)*, *Inflex_location_time_CO_2(CCS)*] there is no demand for hydrogen to mix with the syngas before entering the synthesis process, so there are no investments in electrolyzer capacity and hydrogen storage (Fig. 7d and e and Figure D2, d and g). With limited flexibility in time, as applied in the *Inflex_time, Inflex_location_time, Inflex_time_CO_2(CCS)*, *Inflex_time_CO_2(CCU)*, *Inflex_location_time_CO_2(CCS)*, and *Inflex_location_time_CO_2(CCU)* scenarios, all the units operate continuously with utilization rates close to 100%. Fig. 7f shows that limited flexibility in time results in investments in methanol storage, even with the small operational range (100%–94% of capacity) of the plastics production units due to the low cost of methanol storage. The methanol storage size with limited flexibility in time is 20% lower than the methanol storage size in the *Flex* scenario. Fully inflexible operation, i.e., continuous operation during all hours in a year, will result in no investments being made in methanol storage. It should be noted that the largest methanol storage size is obtained from the modeling results for the *Inflex_location_CO_2(CCU)* scenario (see Figure D2h in Appendix D). In this scenario, there is only one available flexibility option that can be applied in the plastics production process, which is flexibility in time, so the model stimulates investments in methanol storage to achieve flexibility.

Methanol-to-olefins plants have the same locations as the chemical factories, since the chemical factories require a constant supply of olefins, which cannot be stored or transported in the model applied (Figure D1a). As mentioned above, the existing locations and capacities of the chemical factories are used in the model, so these parameters are not varying between the scenarios investigated (Figures D1a and D2f).

3.4. CO_2 utilization

There are two CO_2 utilization modes in the plastics production process: CCU mode, whereby the CO_2 emissions released are utilized to produce plastic; and CCS mode, in which the CO_2 emissions released are captured and stored. It is found that the amount of stored CO_2 is lowest in the *Flex* scenario and highest in the *Inflex_time*, among the scenarios with one limited flexibility option (see Fig. 3). The amount of CO_2 emissions captured from the process is four-fold higher in the *Inflex_time*

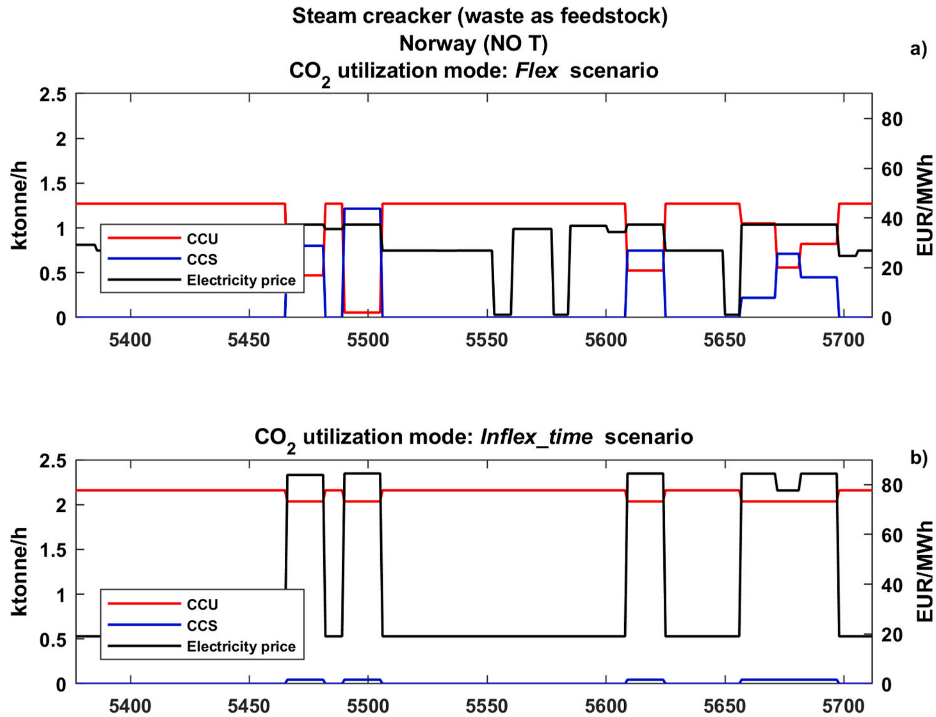

Fig. 9. Electricity price profiles (€/MWh) and CO_2 utilization levels (ktonne) (i.e., CCS and CCU) for steam crackers based on waste for Norway (NO_T) for the *Flex* (a) and *Inflex_time* (b) scenarios for 2 weeks in September. CCS, carbon capture and storage; CCU, carbon capture and utilization.

scenario than in the *Flex* scenario. As mentioned in the *Plastics production cost* section, the reason for this is that flexibility in CO_2 utilization compensates for the limitation of the flexibility in time in the *Inflex_time* scenario. Figs. 8 and 9 present the marginal electricity price profiles and CO_2 utilization modes for the steam cracker based on plastic waste for southern Germany (DE_S), and for the steam cracker based on waste for Norway (NO_T) for the *Flex* (a) and *Inflex_time* (b) scenarios for 2 weeks in September.

Figs. 8a and 9a show that for the *Flex* scenario, CO_2 utilization modes (CCS and CCU) follow the variations in the electricity price in both countries. In southern Germany, CO_2 released from the processing feedstock is stored and captured during high electricity prices of ≥80

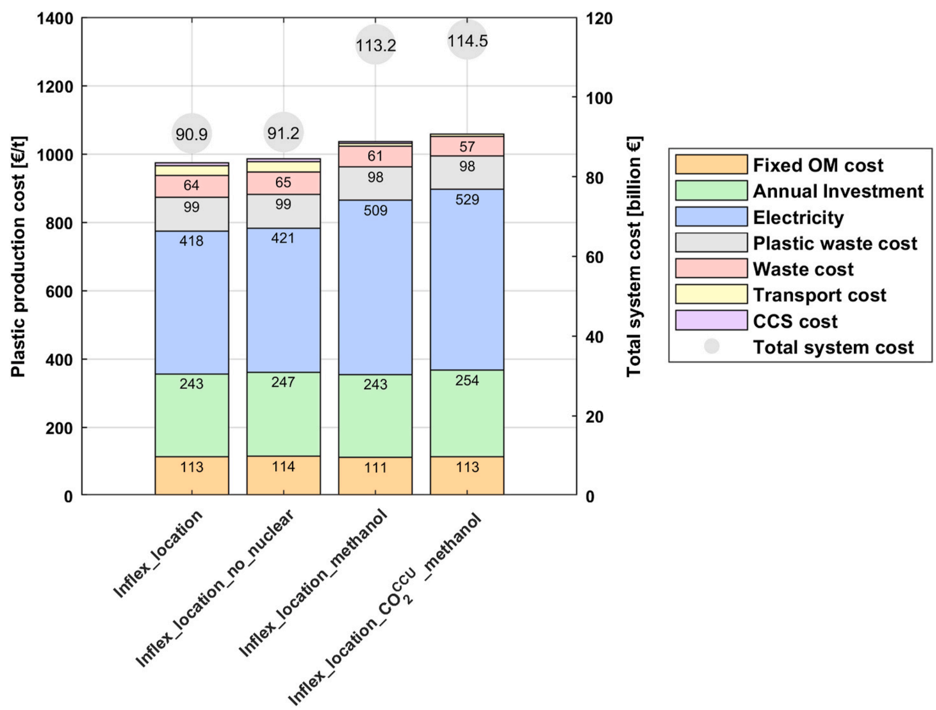

Fig. 10. Breakdown of the modeled plastics production cost into feedstock costs, cost for capture and storage of CO_2, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs (left-hand axis) for the *Inflex_location*, *Inflex_location_NU, Inflex_location_methanol* and *Inflex_location_CO₂(CCU)_methanol* scenarios. The corresponding total system costs are also shown (right-hand axis).

€/MWh (Fig. 8a, Hours 5,500, 5650–5700). When the electricity price varies in the range of 5–40 €/MWh, CO_2 emissions released from the processing feedstock are sent for synthesis to produce methanol. As for Norway, the region with the lowest average electricity price among the regions investigated, the CO_2 emissions are stored and captured when the electricity price is close to or above 40 €/MWh (Fig. 9a, Hours 5500 and 5650). For the *Inflex_time* scenario, when flexibility in time is limited and plastics production units cannot follow variations in the electricity prices, the CO_2 utilization behavior is different in Norway than in southern Germany (Figs. 8 and 9b). The strong availability of low-cost electricity based on hydro and wind power in Norway incentivizes investments in large steam cracker capacity based on waste in this region when there is flexibility as to location. The allocation of the large steam cracker capacity in the *Inflex_time* scenario leads to an increase in the amplitude of the electricity price fluctuation, which is in the range of 20–80 €/MWh, as compared to 5–40 €/MWh for the *Flex* scenario. Yet, CO_2 emissions released from process feedstock are utilized to produce plastic. The steam cracker plant starts to capture and store CO_2 emissions only when the electricity price reaches more than 80 €/MWh (Fig. 9b). As for southern Germany, in the *Inflex_time* scenario, CO_2 emissions are never processed into methanol, although the steam cracker varies the feedstock input to reduce electricity consumption and, for that reason, the CO_2 emissions flow that is captured decreases during periods with electricity prices higher than 80 €/MWh (Fig. 8b).

3.5. Sensitivity analysis: results

The results of the sensitivity analysis are presented in this section. In the first part, the impacts of limiting nuclear power investments in Germany are shown. The second part presents the consequences of the additional methanol production for the investigated system. The third part discusses the effects of the hydrogen storage cost variation on the modeling results. Fig. 10 shows the breakdown of the plastics production cost for the *Inflex_location* scenario (see *Assumptions and scenarios* section), which is the scenario with limited investments in nuclear power in Germany, the *Inflex_location_NU* scenario, and scenarios with additional methanol production, i.e., *Inflex_location_methanol* and *Inflex_location_CO₂(CCU)_methanol* (CO_2 emissions available from feedstock processing used to produce plastics). Electricity generation levels for the electricity system without electrified plastics production (*No_plastic* scenario) and changes in the electricity generation levels for the systems with electricity demands for plastics production under different assumptions [*Inflex_location, Inflex_location_NU, Inflex_location_methanol* and *Inflex_location_CO₂(CCU)_methanol*] are given in Fig. 11. The results for the scenarios in which the hydrogen storage cost varies are given in Appendix C (Figures C1 and C2).

3.5.1. Nuclear power expansion limitation

The limitation regarding investments in nuclear power in Germany, as applied in the *Inflex_location_NU* scenario, gives an increase in electricity generation from nuclear power of 25 TWh (66%) compared to the *No_plastic* scenario, whereas the *Inflex_location* scenario gives a 156 TWh (400%) increase. In the *Inflex_location_NU* scenario, the additional electricity generation needed to satisfy the electricity demand for plastics production comes from wind and solar power. For the *Inflex_location_NU* scenario, electricity production from wind and solar power increases by 8% and 7%, respectively, as compared to the *Inflex_location* scenario. The plastics production cost in *Inflex_location_NU* increases by 1% compared to the *Inflex_location* scenario, with the main increase attributed to investment and electricity costs. The lack of nuclear power in the electricity mix stimulates investments in overcapacity of the plastics production units. In the *Inflex_location_NU* scenario, the electrolyzer capacity increases by 3% and the steam cracker and synthesis plant capacities increase by 1%, as compared to the obtained capacities in the *Inflex_location* scenario.

3.5.2. Additional methanol production

Additional methanol production is introduced to utilize all the carbon available in the system. This additional production of methanol, as applied in the *Inflex_location_methanol* and *Inflex_location_CO₂(CCU)_methanol* scenarios, results in plastics production cost increases of 8% and 17%, respectively, as compared to the *Inflex_location* scenario. The

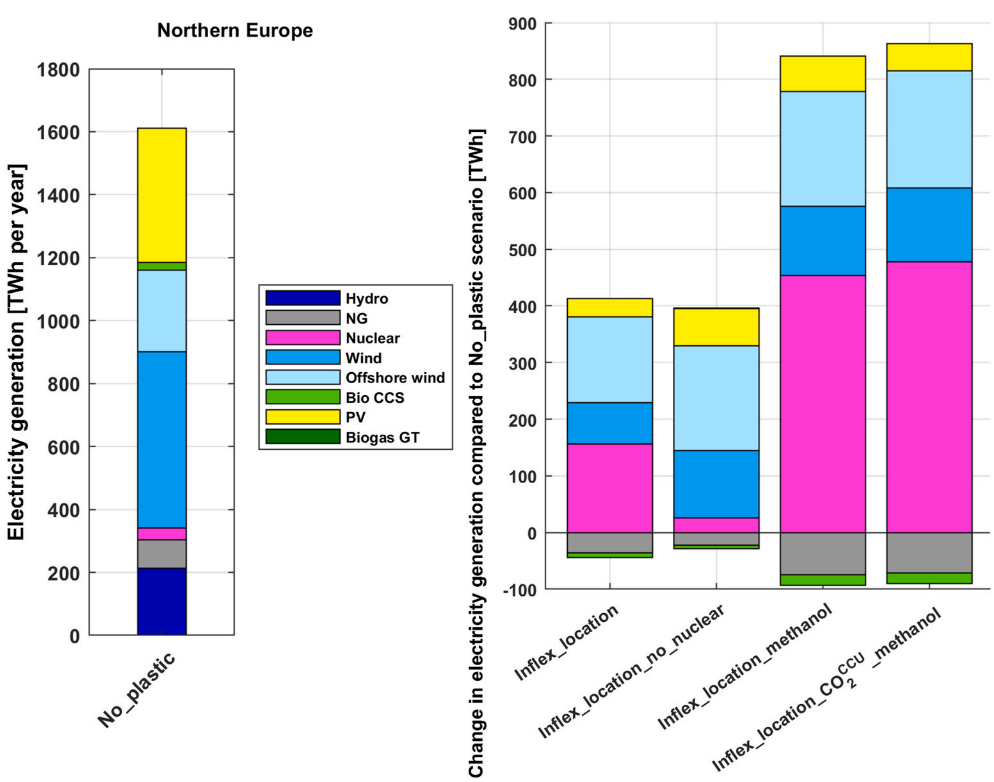

Fig. 11. Total annual electricity generation (in TWh) for the scenario without electrified plastics production (left-hand panel) and the differences (in TWh) in electricity generation between an electricity system without electrified plastics production and the scenarios with electrified plastics production, i.e., the *Inflex_location, Inflex_location_NU, Inflex_location_methanol* and *Inflex_location_CO₂(CCU)_methanol* scenarios (right-hand panel). NG, natural gas; GT, gas turbine; Bio, biomass; CCS, carbon capture and storage; PV, photovoltaic.

largest increases in plastics production costs arise from the electricity cost, which are 22% and 27% in the *Inflex_location_methanol* and *Inflex_location_CO_2(CCU)_methanol* scenarios, respectively. To satisfy the electricity demands from the methanol and plastics production processes, electricity generation increases by 15% and 25% for the *Inflex_location_methanol* and *Inflex_location_CO_2(CCU)_methanol* scenarios, respectively, as compared to the *No_plastic* scenario. Electricity generation from wind and solar power contributes the biggest share (74%) of the electricity mix in both scenarios.

3.5.3. Hydrogen storage costs variation

The cost of hydrogen storage was decreased and increased by 50% and 90%, respectively, as compared to the cost applied in the scenario with limited flexibility regarding location, i.e., the *Inflex_location* scenario. The impact of the hydrogen storage cost change on the plastics production cost is low, i.e., a 2% decrease in the cost of plastics production for the *Inflex_location_decrease_90* scenario and a less than 1% increase for the *Inflex_location_increase_90* scenario, as compared to the plastics production cost obtained from the *Inflex_location* scenario (Figure C1 in Appendix C). A reduction of the hydrogen storage cost promotes the CO_2 utilization mode when all the CO_2 emissions released from the feedstock processing are used to produce plastics. From Figure C1 in Appendix C, it is evident that the costs for waste and CCS decline together with the hydrogen storage costs, i.e., carbon recovery from the feedstock is higher when there is a possibility to store hydrogen at a lower price. With a higher cost for hydrogen storage, the flexibility of the hydrogen production process in time is reduced, and this incentivizes investments in nuclear power. Nuclear power generation is four-times higher in the *Inflex_location* scenario than in the *No_plastic* scenario. With a 90% increase in the cost of hydrogen storage, the nuclear power generation is five-times higher than in the *No_plastic* scenario (see Figure C2; Appendix C).

4. Discussion

The strong connection between the system for plastics production and the petroleum industry results in a strong carbon lock-in at different points of the value chain, and this has been highlighted as a significant barrier to low-carbon innovation (Bauer et al., 2018). If other carbon-intensive sectors, such as the electricity system, the transport sector and the steel industry, implement their already existing strategies to reach zero emissions, the plastics and chemicals industries will account for an increased share of the remaining emissions. As a result, heavy pressure will be exerted on the plastics industry to break the carbon lock-in. Strategies and targets that are aligned with climate policy objectives are needed for the plastics sector, as well as for individual chemical clusters and corporations, to break the carbon lock-in. In addition, government policy plays an important role in reshaping markets and improving waste management (Bauer et al., 2022). Thermochemical waste processing solutions make zero-carbon targets possible in the plastics production sector, while resolving the plastic waste problem and paving the way for a circular economy. The main obstacles to large-scale implementation of thermochemical waste processing solutions are the difficulties related to monetization of the environmental benefits arising from the use of these solutions (Porshnov, 2022) and a lack of clarity regarding the economic feasibility levels of the various recycling approaches. The current fragmentation of the value chain and the regional nature of waste-management systems represent additional barriers to progress (McKinsey, 2022).

One of the main assumptions used in the present study is net-zero CO_2 emissions for the modeled system (electricity system and plastics sector). The assumption is motivated by political goals, such as the Paris Agreement (UNFCC, 2015) and the European Green Deal (EC, 2019). Furthermore, a greenfield approach is applied to a year that represents the net-zero emissions electricity system. The greenfield approach applied in this model ignores the restrictions imposed by existing systems, assuming that every technology is built from scratch. Neglecting these restrictions can be motivated by the observation that almost all of the current electricity generation and plastics production capacities need to be replaced to reach the set goals. With a greenfield approach, an optimal solution that is possibly hidden behind today's system structures can be found (Kienzle and Andersson, 2009). The results obtained from the modeling reveal benchmarks for an optimized future system.

The amount of carbon in waste that is currently incinerated each year in Europe in waste-to-energy plants varies in the range of 27–54 Mt. This carbon can be used to produce 32–64 Mt of plastic products, assuming 85% carbon content of the plastic product, and can satisfy the current demand for plastics in Europe (51 Mt) (PlasticsEurope, 2020). The alternative to the plastics production process proposed in this study is a process in which plastic is produced through capturing and utilizing the CO_2 emissions released by the existing waste incineration plants. Despite the savings in investments that this would entail (given the existing infrastructure), the production cost for the process when plastic is produced via the utilization of the CO_2 from waste incineration is higher than it is via the waste gasification process (Fig. 1). The main increase in the cost of plastics production, when CO_2 emissions from waste incineration are utilized, is linked to the high hydrogen demand, resulting in high electricity consumption and investments in electrolyzer overcapacity to avoid high electricity prices (see Appendix E). The value of waste heat is not included in the cost comparison.

In December 2019, the EC excluded waste-to-energy incineration from a list of economic activities considered as advanced climate change mitigation, stating that minimizing incineration and avoiding waste disposal will contribute to a carbon-neutral and circular economy (Vilella, 2019). This decision represents a significant risk to the future financial viability of incineration plant projects. The process proposed and investigated in the present study could pave the way for current waste incineration facilities to redesign and transform their operations while using the existing logistics and infrastructure. However, the transition of waste management practices from incineration to recycling raises challenges for the heat sector in Europe, i.e., a heat supply deficit. This means that the shift to the circular economy necessitates not only electricity system transformation, i.e., decarbonization of the electricity supply, but also concomitant heat sector transformation.

Due to the rapid decline in the cost of renewable electricity, electricity and green hydrogen are attractive options for industries that are striving to decarbonize their processes (de Bruyn et al., 2020; Lechtenböhmer et al., 2016). This work investigates the impacts of electrification from the electricity system perspective, as well as from the electricity consumer perspective. The sensitivity analysis of a situation in which the production of methanol is introduced into the system to utilize the total carbon available in the system, shows that the new electricity demand increases the plastics production cost by up to 17%, as compared to the scenario without addition methanol production. These results highlight the importance of energy conservation in energy-intensive industries. Yet, the plastics production cost in the scenario with additional electricity demand for methanol production is cheaper than in the scenario with the limitation regarding time flexibility. This result underlines the importance of time flexibility for the electricity-intense industrial consumer. Further research is needed to investigate the combined effects of electrified energy-intensive industries on the electricity system.

5. Conclusions

A cost-minimizing electricity system investment model was applied to investigate the interactions between the electricity system and electrified production of plastics (thermochemical plastic recycling and waste gasification), taking into consideration different flexibility options for the plastics production process. Under the assumptions made, it is clear that satisfying the current demand for plastic products in northern

Europe through electrified thermochemical recycling and waste gasification processes will increase the electricity demand by 240–400 TWh. With the aim of attaining net-zero CO_2 emissions in the investigated system, the additional electricity demand to produce plastics is mainly covered by increased generation from wind and nuclear power, while this reduces the production of electricity from natural gas-based generation technologies. The share of renewable energy (wind and solar power) in the modeled electricity system mix for all the investigated scenarios is in the range of 74%–78%. The modeling results show that the cost of electricity accounts for the largest fraction (30%–57%) of the plastics production cost in all the scenarios, followed by the annualized investment cost (18%–26%). The two main factors that define the location of electrified plastics production units (under the assumptions made herein) are the availability of large volumes of waste and favorable conditions for low-cost electricity.

Full flexibility (flexibility in regards to time and location, and flexibility of CO_2 utilization) of the plastics production process yields: 1) the lowest plastics production cost; 2) the highest rate of carbon recovery from the feedstock among the scenarios without limitation as to CO_2 utilization; and 3) the lowest capacity utilization rate, i.e., there is an investment in overcapacity to achieve flexibility. A limitation as to location flexibility (i.e., no export of waste is allowed) increases imports of electricity to the waste-rich regions. Time flexibility is found to have a stronger impact on the cost of plastics, and scenarios with time flexibility limitations exhibit the highest costs for production of plastics among the scenarios investigated. With limited flexibility in time, the plastics production units are allocated to regions with a low average electricity cost and all the CO_2 emissions from the process are captured and stored.

CRediT authorship contribution statement

Alla Toktarova: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, preparation, Writing – review & editing. **Lisa Göransson:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Henrik Thunman:** Conceptualization, Writing – review & editing, Project administration, Funding acquisition. **Filip Johnsson:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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Appendix

Appendix A

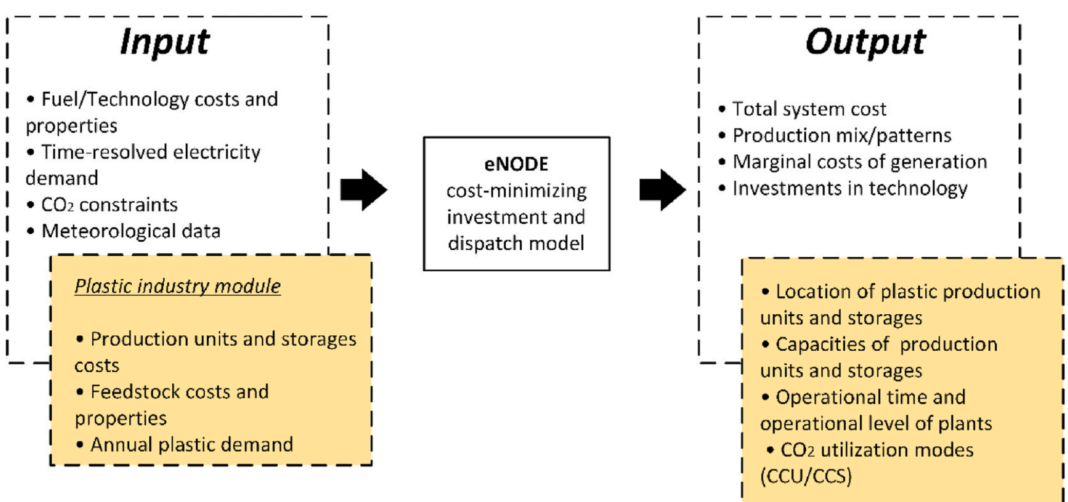

Fig. A1. Schematic overview of the model used in this work.

Thermochemical plastics recycling and waste gasification process modeling are described in this section. All the sets, parameters and variables are described in this section and listed in Table A1. Equations (1)–(7) describe the mass balance relations between the plastics production units. Equation (1) gives the mass balance for the feedstock used for plastics production (plastic waste and waste). On an annual basis, the available feedstock is larger than that produced by-products (olefins, syngas, CO_2), as well as exported feedstock.

$$x_{p_{cracker},r} \geq \sum_{t \in T} \left(g_{p_{cracker},t,r} m + \sum_{r_2 \in R} e_{p_{cracker},t,r,r_2} \right) \quad \forall r \in R \tag{1}$$

Equation (2) gives the syngas balance. The by-products (CO and $H_2$from the cracking process, as well as CO_2 emissions) are produced from cracking feedstock in the steam cracker and are used for methanol production in the synthesis plant.

$$\sum_{p \in P^{cracker}} \left(g_{p,t,r} q_p + b_{p,t}^{synthesis}\right) \geq g_{P^{Synthesis},t,r}$$
$$\forall t \in T, \forall r \in R \tag{2}$$

Equation (3) represents the H_2 balance. Hydrogen is produced in the electrolyzer and used to balance the H_2 content of the syngas. The syngas is synthesized into methanol.

$$g_{P^{Electrolyser},t,r} + \sum_{p \in P^{H_2}} z_{p,t,r}^{dis} \geq \sum_{p \in P^{cracker}} b_{p,t}^{synthesis} a + \sum_{p \in P^{H_2}} z_{p,t,r}^{ch}$$
$$\forall t \in T, \forall r \in R \tag{3}$$

The CO_2 emissions released from the feedstock cracking can be captured and converted to methanol through a synthesis process; alternatively, they can be captured and stored [Eq. (4)].

$$g_{P^{cracker},t,r} n_p \geq b_{p,t}^{synthesis} + b_{p,t}^{CCS}$$
$$p \in P^{cracker}, \forall t \in T, \forall r \in R \tag{4}$$

Equation (5) gives the mass balance for methanol. Methanol is produced in the synthesis plant and processed into olefins in the methanol-to-olefins unit. The free variable $e_{p^{synthesis},t,r,r_2}$ represents the export of methanol from region r to region r_2 (a negative value implies methanol import).

$$g_{P^{synthesis},t,r} + z_{P^{methanol},t,r}^{dis} \geq g_{P^{MTO},t,r} + z_{P^{methanol},t,r}^{ch} + \sum_{r_2 \in R} e_{P^{synthesis},t,r,r_2}$$
$$\forall t \in T, \forall r \in R \tag{5}$$

Equation (6) presents the olefins balance. The production levels of olefins from plastic waste cracking and from syngas synthesis are higher than in the demand of the chemical factories for olefins.

$$\sum_{p \in P^{cracker}} g_{p,t,r} o_p + g_{P^{MTO},t,r} \geq g_{P^{CF},t,r}$$
$$\forall t \in T, \forall r \in R \tag{6}$$

Demand-supply constraints [Eq. (7)] ensure that the plastics production capacity (in terms of the chemical factories) produces sufficient levels of plastic products, as needed to satisfy the total annual demand for plastics in each region. The free variable e_{P^{CF},t,r,r_2} represents export of plastics from region r to region r_2, whereas import of plastics is represented by a negative value.

$$\sum_{t \in T} g_{P^{CF},t,r} \geq s_r + \sum_{t \in T} \sum_{r_2 \in R} e_{P^{CF},t,r,r_2}$$
$$\forall r \in R \tag{7}$$

Equation (8a) ensures that the levels of electricity generation, commodity production, transmission, and stored products do not exceed the installed capacity. For wind and solar power, the installed capacity is weighted by weather-dependent profiles ($W_{p,t,r}$). The $W_{p,t,r}$ equals one in the case of all other technologies.

$$g_{p,t,r} \leq i_{p,r} W_{p,t,r}$$
$$p \in P, \forall t \in T, \forall r \in R \tag{8a}$$

Equation (8b) limits the operations of plastics production technologies. For the steam cracker, the steam reformer and the methanol-to-olefins process, the output can fluctuate within the operational range of 100%–50% capacity. The operation of the synthesis process can be reduced to 25% of full capacity.

$$g_{p,t,r} \geq i_{p,r} W_{p,t,r} k$$
$$p \in P^{Plastic}, \forall t \in T, \forall r \in \tag{8b}$$

The balance constraints for storage are given in Eq. (9).

$$g_{p,t,r} = g_{p,t,r-1} + \eta_p z_{p,t,r}^{ch} - z_{p,t,r}^{dis}$$
$$p \in P^{STR}, \forall t \in T, \forall r \in R, \tag{9}$$

Table A1 includes all the sets, parameters and variables used in the model.

Table A1
Notations for the model description.

Sets	
R	is the set of all regions
P	is the set of all technologies
P^{el}	is a subset of P that includes all electricity generation technologies
P^{transm}	is a subset of P that includes transmission lines
P^{STR}	is a subset of P that includes storages
$P^{methanol}$	is a subset of P that includes methanol storage
P^{H_2}	is a subset of P that includes H_2 storage
$P^{plastic}$	is a subset of P that includes the steam cracker, steam reformer, synthesis plant, electrolyzer, methanol-to-olefins unit and chemical plant
$P^{electrolyser}$	is a subset of P that includes the electrolyzer
$P^{cracker}$	is a subset of P that includes the steam crackers
	is a subset of P that includes synthesis

(continued on next page)

Table A1 (*continued*)

Sets	
$P^{synthesis}$	
P^{MTO}	is a subset of P that includes the methanol-to-olefins unit
P^{CF}	is a subset of P that includes the chemical plant
T	is the set of all time-steps
Variables	
$b_{p,t}^{CCS}$	is the CO_2 emissions from technology $p \in P^{plastic}$ that are captured and stored
$b_{p,t}^{synthesis}$	is the CO_2 emissions from technology $p \in P^{plastic}$ that are synthesized
C^{tot}	is the total system cost
C_p^{inv}	is the annualized investment cost of technology p in region r
$C_p^{O\&M,fix}$	is the fixed operations and maintenance costs of technology p
$C_{p,t}^{cycl}$	is the cycling cost of technology p at time-step t
$C_{p,t}^{run}$	is the running cost of technology p at time-step t
C^{st}	is the cost of capturing and storing CO_2 emissions
C_{r,r_2}^{transp}	is the cost of transportation between regions r and r_2
e_{p,t,r,r_2}	is a free variable representing the export of product that is transmitted/produced by technology $p \in P^{transm} \cup P^{plastic}$ between regions r and r_2 at time-step t
e_{p,t,r,r_2}^{pos}	is the positive variable consistent with $e_{p,t,r,r_2}^{pos} \geq e_{p,t,r,r_2}$
$g_{p,t,r}$	is the generation of electricity, production of commodities and the state-of-charge of storage for technology p at time-step t in region r
$i_{p,r}$	is the capacity investment in technology p, in region r
$z_{p,t,r}^{dis}$	is the discharging of storage technology p at time-step t in region r
$z_{p,t,r}^{ch}$	is the charging of storage technology p at time-step t in region r
Parameters	
a	is the coefficient applied to relate methanol production to H_2 demand to utilize CO_2 emissions $b_{p,t}^{synthesis}$ in a synthesis plant
$D_{r,t}$	is the historical electricity demand at time-step t in region r
f_p	is the electricity demand of technology $p \in P^{plastic}$
k	is the coefficient applied to present operation range of plastics production technologies $P^{plastic}$
m	is the coefficient applied to relate carbon content of the feedstock to the carbon content in the plastic products
n_p	is the share of CO_2 emissions in the by-products produced from technology $p \in P^{plastic}$
o_p	is the share of olefins in the by-products produced from technology $p \in P^{plastic}$
q_p	is the share of syngas in the by-products produced from technology $p \in P^{plastic}$
s_r	is the plastic demand in region r
$W_{p,t,r}$	is the profile limiting the weather-dependent generation of technology p in time-step t in region r
$x_{p,r}$	is the feedstock availability and initial distribution (see *Investigated scenarios*) in region r for technology p

Appendix B

The wind and solar supply profiles and available capacities for different resource classes are calculated based on (Mattsson et al., 2021). Table B1 gives the investments and running costs for the electricity generation technologies and plastics production technologies considered in the model. The annualized investment costs are applied assuming a 5% interest rate and technical lifetimes.

Table B1
Costs and technical data for the electricity generation technologies and plastics production technologies.

	Lifetime, [years]	Investment cost, [€/kW$_{el}$]	Fixed O&M cost, [€/kW$_{el}$/yr]	Variable O&M cost, [€/kW$_{el}$/yr]	Efficiency, [%]	Minimum load level, [share of rated power]	Start-up time, [h]	Start-up cost, [€/MW]
Biomass[a]								
Condenser	40	2000	52	2.1	35	0.35	12	57
CCGT	30	900	17	0.8	61	0.2	6	43
GT	30	450	15	0.4	42	0.2	0	20
BECCS	40	3218	123	2.1	27	0.35	12	57
Intermittent[b]								
Solar PV	40	418	7	0.5	100	–	–	–
Offshore wind	30	1531	36	1.1	100	–	–	–
Onshore wind	30	961	13	1.1	100	–	–	–
Natural gas[a]								
CCGT	30	900	13	0.8	61	0.2	0	43
CCS	30	1575	35	0.8	54	0.35	12	57
GT	30	450	8	0.8	42	0.5	0	20
Nuclear[c]								
Nuclear	60	4124	95	6.6	33	0.9	24	400
Storage[b]								
H_2 cave storage	40	11	–	–	100	–	–	–
Li-ion batteries	15	135	0.27	–	95	–	–	–
Methanol storage[d]	40	10	–	–	100	–	–	–

(*continued on next page*)

Table B1 (*continued*)

	Lifetime, [years]	Investment cost, [€/kW$_{el}$]	Fixed O&M cost, [€/kW$_{el}$/yr]	Variable O&M cost, [€/kW$_{el}$/yr]	Efficiency, [%]	Minimum load level, [share of rated power]	Start-up time, [h]	Start-up cost, [€/MW]
Plastic[e]								
Steam cracker	30	1110	33	–	–	0.5	–	–
Steam reformer	30	1354	41	–	–	0.5	–	–
Synthesis	30	864	26	–	–	0.25	–	–
MTO	30	689	21	–	–	0.5	–	–
Electrolyzer[b]	20	500	24	–	79	–	–	–

BECCS, bio-energy carbon capture and storage; CCGT, combined cycle gas turbine; GT, gas turbine; MTO, methanol-to-olefins unit.

[a] The values for the investment costs and the fixed/variable O&M costs for electricity generation technologies are taken from World Energy Outlook assumptions of the IEA, Year 2021 edition (IEA, 2021). Investment costs for CCS technologies are obtained from the Zero Emission Platform (ZEP, 2011).

[b] The values for investment costs and the fixed/variable O&M costs for solar and wind power, hydrogen storage, batteries and electrolyzer are obtained from (Danish Energy Agency, 2021). The costs for hydrogen storage are given per kWh.

[c] The values for investment costs and the fixed/variable O&M costs are obtained from (Kan et al., 2020; Sepulveda et al., 2018).

[d] The values for investment costs of methanol storage are taken from (Dias et al., 2020); the costs are given per tonne.

[e] The values for investment costs of the plastics production units are taken from (Thunman et al., 2019). The units are per tonne-year. The fixed O&M costs are assumed to be 3% of the total CAPEX.

Table B2

Locations and capacities of the chemical factories.

Regions	BAL	DE_N	DE_S	FI	IE_T	NO_T	PO3	PO_S	SE_N	SE_S	UK1	UK2
Capacity of chemical factories, [million tonnes per year]	0	17	3.5	0.6	0	0.6	0.7	0	0	1.2	1.2	1.9

The data for the capacities of chemical factories in Europe are taken from (ICIS, 2022; INEOS, 2022; Petrochemicals Europe, 2022).

Table B3

Assumed annual levels and locations for plastic demand, plastic waste and waste.

Regions	BAL	DE_N	DE_S	FI	IE_T	NO_T	PO3	PO_S	SE_N	SE_S	UK1	UK2
Plastics demand[a], [million tonnes per year]	0.6	7.5	8.6	0.4	0.4	0.3	1.1	2.6	0.2	1.3	3.1	0.3
Plastic waste [a,b], [million tonnes per year]	0.2	1.8	2.4	0.1	0.3	0.2	0.3	0.3	0.1	0.4	2.1	0.2
Waste[c], [million tonnes per year]	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

[a] The data for plastic demand and plastic waste production are taken from (PlasticsEurope, 2020).

[b] The plastic packaging waste currently (2020) collected in Europe is considered as plastic waste.

[c] Available amount of waste and its locations are taken from (Stengler, 2019).

The amount of carbon in the produced plastic product is assumed to be 85%$_{wt}$ (VELA, 2022). The maximum amount of carbon that can be extracted from plastic waste is assumed to be 85%$_{wt}$ (Thunman et al., 2019). The characteristics of waste are taken from (Mazzoni et al., 2017; Nemmour et al., 2022; Valkenburg et al., 2008). The carbon content of dry and ash-free waste is assumed to be 60%$_{wt}$.

Appendix C

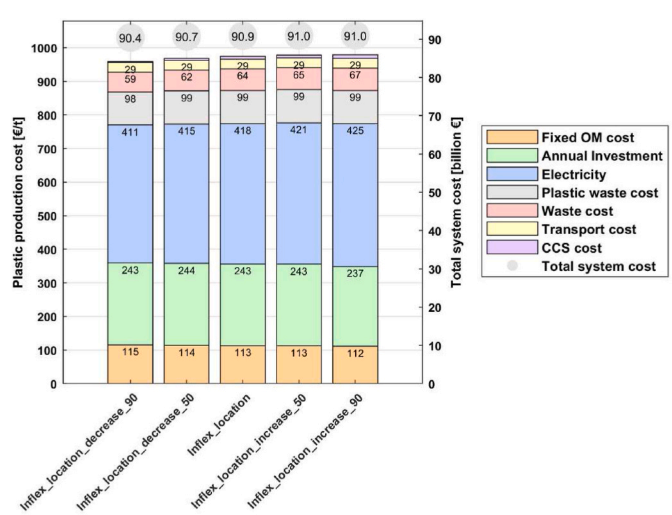

Fig. C1. Breakdown of the modeled plastics production cost into feedstock costs, costs for capture and storage of CO_2, annualized investment cost, fixed O&M costs, electricity cost, and transportation costs (left-hand axis) for the scenarios with limitations as to location. The corresponding total system costs are also shown (right-hand axis). The cost of hydrogen storage varies between the scenarios, i.e., decreases and increases by 50% and 90%, respectively, as compared to the cost applied in the scenario with limited flexibility as to location: the *Inflex_location* scenario. The scenarios in which the hydrogen storage cost varies are termed: *Inflex_location_decrease_90*, *Inflex_location_decrease_50*, *Inflex_location_increase_50* and *Inflex_location_increase_90*.

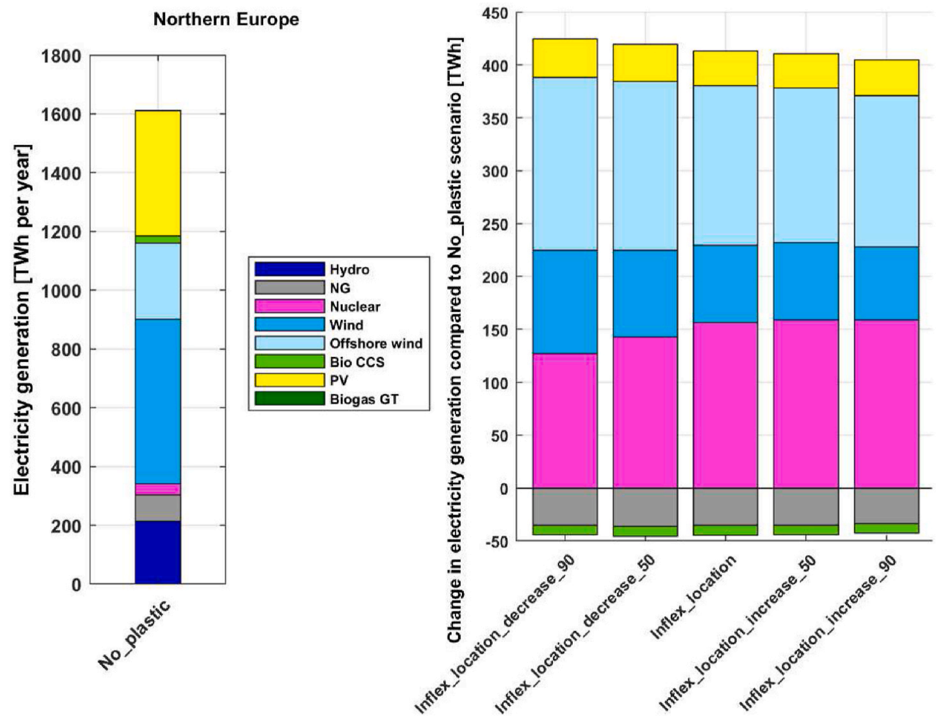

Fig. C2. Total annual electricity generation (in TWh) for the scenario without electrified plastics production (left-hand panel), and the differences (in TWh) in electricity generation between an electricity system without electrified plastics production and the scenarios with electrified plastics production and no export of waste between regions (right-hand panel). The cost of hydrogen storage varies between the scenarios, i.e., decreases and increases by 50% and 90%, respectively, as compared to the cost applied in the scenario with limitations regarding flexibility of location: the *Inflex_location* scenario. The scenarios in which the hydrogen storage cost varies are termed: *Inflex_location_decrease_90*, *Inflex_location_decrease_50*, *Inflex_location_increase_50* and *Inflex_location_increase_90*. NG, natural gas; GT, gas turbine; Bio, biomass; CCS, carbon capture and storage; PV, photovoltaic.

Appendix D

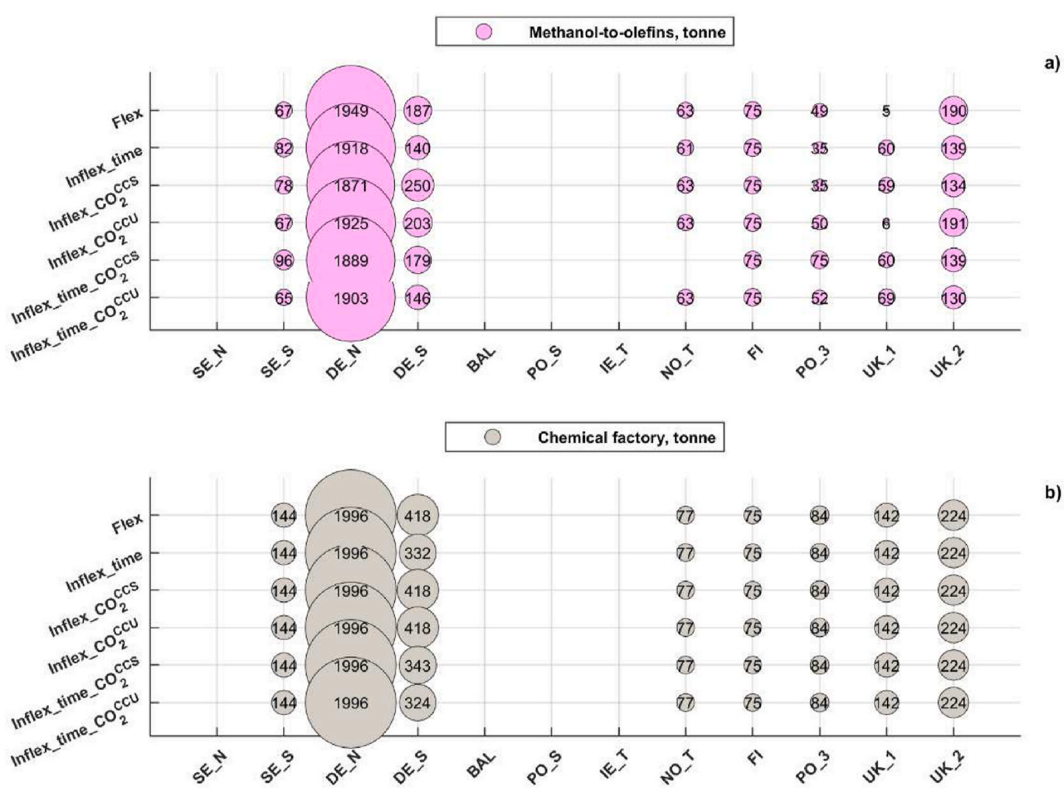

Fig. D1. The modeling results for the scenarios without limitation regarding flexibility of location [*Flex, Inflex_time, Inflex_CO$_2$(CCS), Inflex_CO$_2$(CCU), Inflex_time_CO$_2$(CCS), Inflex_time_CO$_2$(CCU)*]. The regional allocations of the plastics production capacities are given in terms of the methanol-to-olefins units in ktonne (a) and for the chemical factories in ktonne (b).

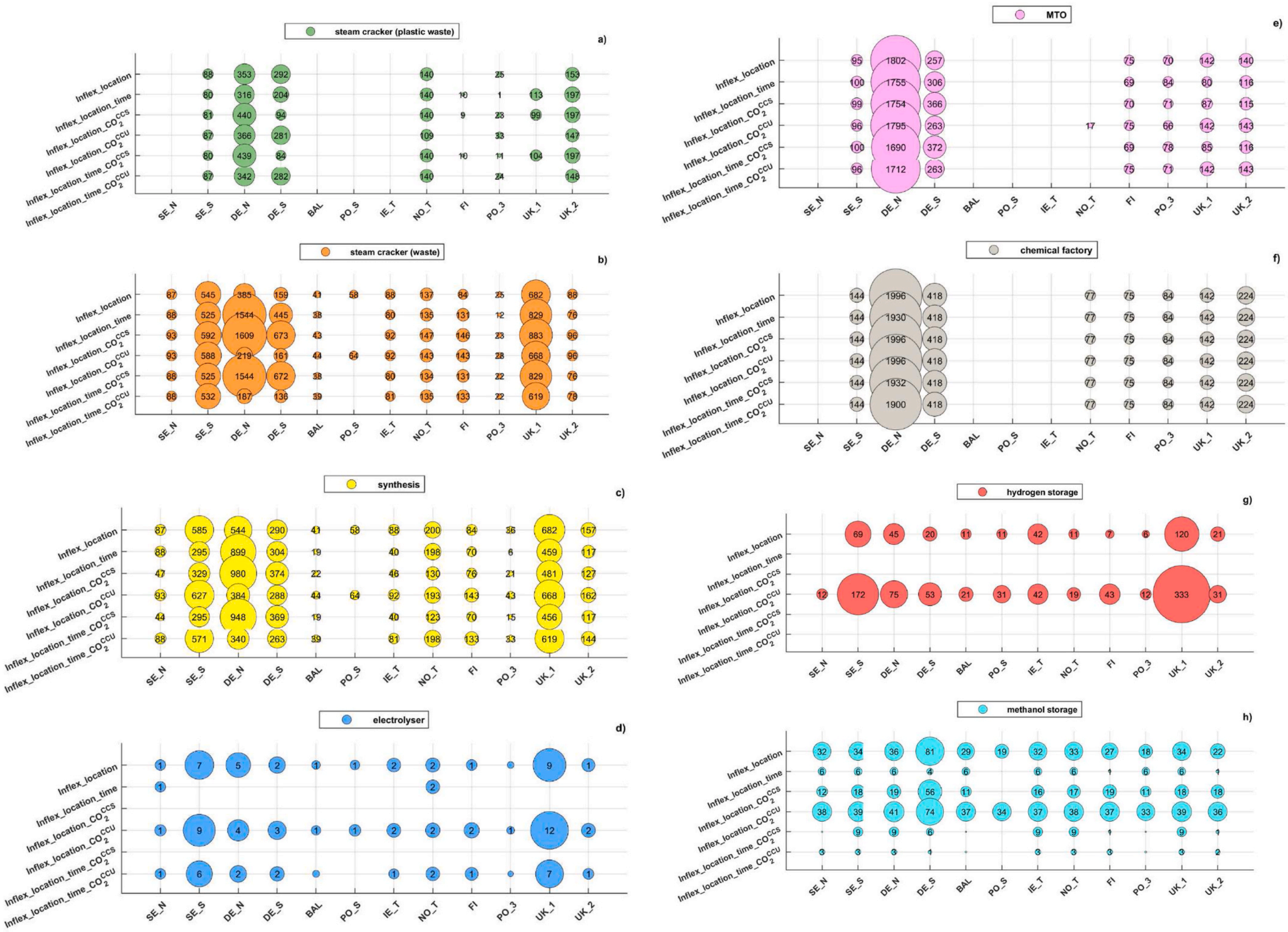

Fig. D2. The modeling results for the scenarios without limitation regarding flexibility of location [*Flex, Inflex_time*, *Inflex_CO₂(CCS)*, *Inflex_CO₂(CCU)*, *Inflex_time_CO₂(CCS), Inflex_time_CO₂(CCU)*]. The regional allocations of the plastics production capacities are given in terms of the stream crackers in ktonne (a and b), synthesis plant in ktonne (c), electrolyzer in GW (d), methanol-to-olefins unit in ktonne (e), chemical factories in ktonne (f), hydrogen storage in GWh (g) and methanol storage in ktonne (h).

Appendix E

The supplementary investigated scenarios (*Flex_WtE and Flex_WtE_CO_2storage*) are presented in this section. Plastics production is assumed to occur through thermochemical recycling of plastic waste and utilization of the CO_2 stream from waste incineration (Route 2 from Table 1 is replaced by Route E2 from Table E1). The current locations and capacities of the waste incineration plants are used in the investigation scenarios (Table B2). It is assumed that the waste incineration plants will be retrofitted with a CCS unit, i.e., there is no investment cost for the waste incineration plants. The investment cost for the CCS unit is taken from (Garðarsdóttir et al., 2018). The electricity demand of the carbon capture unit is taken from (Roussanaly et al., 2020). Carbon stream utilization occurs via the processes described in the *Process description* section.

Table E1
Overview of the configurations for plastics production processes applied in the supplemental scenarios.

	Route 1	Route E2
Feedstock	Plastic waste	Waste mix
Process	Thermochemical: recycling	Thermochemical: incineration
Technology	Steam cracker (Fluidized bed reactor)	Waste-to-energy (WtE) plant
Configuration*	Fully electrified	WtE with CCS and fully electrified downstream processes

The *Flex_WtE* scenario has full flexibility, i.e., flexibility with regards to time and location, and flexibility of CO_2 utilization (cf. *Assumptions and scenarios*). For the *Flex_WtE_CO_2storage* scenario, an additional flexibility option is considered: the stored CO_2 emissions can be synthesized. The investment costs for CO_2 storage are taken from (Smith et al., 2021). The modeling results for the *Flex_WtE* and *Flex_WtE_CO_2storage* scenarios are compared to those for the *Flex* scenarios (Fig. 2).

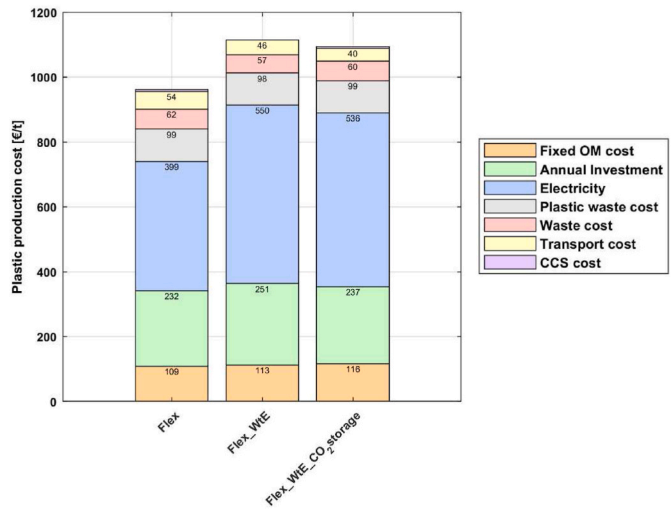

Fig. E1. Breakdown of the modeled plastics production cost into feedstock costs, cost of capture and storage of CO_2, the annualized investment cost, the fixed O&M costs, electricity cost, and transportation costs for the *Flex*, *Flex_WtE* and *Flex_WtE_CO₂storage* scenarios.

The modeling results indicate that under the given assumptions, the plastics production cost is 16% higher in the *Flex_WtE* scenario, i.e., when the CO_2 emissions from the existing waste incineration plants are utilized, as compared to the plastics production cost in the *Flex* scenario. The increase in hydrogen demand related to the utilization of CO_2 emissions causes the electricity cost to rise in the *Flex_WtE* scenario. The electrolyzer overcapacity needed to avoid electricity consumption during high-net-load events gives rise to the investment costs in the *Flex_WtE* scenario, as compared with the *Flex* scenario. The usage of CO_2 storage to render the supply of the CO_2 emissions into the synthesis plant flexible, as applied in the *Flex_WtE_CO$_2$storage* scenario, can reduce plastics production costs by 2%, as compared to the *Flex_WtE* scenario. It should be mentioned here that the benefits accrued from the heat and electricity produced by the waste-to-energy plants are not considered in the investigated scenarios.

References

Al-Salem, S.M., Behbehani, M.H., Al-Hazza'a, A., Arnold, J.C., Alston, S.M., Al-Rowaih, A.A., Asiri, F., Al-Rowaih, S.F., Karam, H., 2019. Study of the degradation profile for virgin linear low-density polyethylene (LLDPE) and polyolefin (PO) plastic waste blends. J. Mater. Cycles Waste Manag. 21, 1106–1122.

Aracil, C., Haro, P., Giuntoli, J., Ollero, P., 2017. Proving the climate benefit in the production of biofuels from municipal solid waste refuse in Europe. J. Clean. Prod. 142, 2887–2900.

Arena, U., Zaccariello, L., Mastellone, M.L., 2010. Fluidized bed gasification of waste-derived fuels. Waste Manag. 30, 1212–1219.

BASF, 2022. BASF, SABIC and Linde Join Forces to Realize the World's First Electrically Heated Steam Cracker Furnace.

Bauer, F., Ericsson, K., Hasselbalch, J., Nielsen, T., Nilsson, L.J., 2018. Climate Innovations in the Plastic Industry: Prospects for Decarbonisation.

Bauer, F., Nielsen, T.D., Nilsson, L.J., Palm, E., Ericsson, K., Fråne, A., Cullen, J., 2022. Plastics and climate change breaking carbon lock-ins through three mitigation pathways. One Earth 5, 361–376.

Calvin, K., Cowie, A., Berndes, G., Arneth, A., Cherubini, F., Portugal-Pereira, J., Grassi, G., House, J., Johnson, F.X., Popp, A., 2021. Bioenergy for climate change mitigation: scale and sustainability. GCB Bioenergy 13, 1346–1371.

Chen, C., Yang, A., Bañares-Alcántara, R., 2021. Renewable methanol production: understanding the interplay between storage sizing, renewable mix and dispatchable energy price. Adv. Appl. Energy 2, 100021.

Danish Energy Agency, 2021. Technology Data.

de Bruyn, S., Jongsma, C., Kampman, B., Görlach, B., Thie, J.E., 2020. Energy-intensive industries. Challenges and opportunities in energy transition. CE Delft, Eur. Parliam. Comm. Ind. Res. Energy.

Dias, V., Pochet, M., Contino, F., Jeanmart, H., 2020. Energy and economic costs of chemical storage. Front. Mech. Eng. 6, 21.

Dow, 2022. Dow Benelux outlines roadmap to support Dutch Climate Agreement, achieve CO2 emissions neutrality [WWW Document]. URL. https://investors.dow.com/en/news/news-details/2021/Dow-Benelux-outlines-roadmap-to-support-Dutch-Climate-Agreement-achieve-CO2-emissions-neutrality/default.aspx (accessed 5.30.22).

Ec, 2021. Proposal for a REGULATION of the EUROPEAN PARLIAMENT and of the COUNCIL on Shipments of Waste and Amending Regulations (EU) No 1257/2013 and (EU) No 2020/1056.

Ec, 2019. The European Green Deal.

Ec, 2018. A European strategy for plastics in a circular economy. Commun. from Comm. to Eur. Parliam.

Ec, 2015. Closing the loop-An EU action plan for the Circular Economy. Commun. from Comm. to Eur. Parliam. Counc. Eur. Econ. Soc. Comm. Comm. Reg. COM 614, 2015.

Entso-E, 2017. Hourly load values for a specific country for a specific Month (in MW). WWW Document]. URL. https://www.entsoe.eu/data/power-stats/hourly_load/h.

EU, 2020. Circular Economy Action Plan for a Cleaner and More Competitive Europe.

Eurostat, 2022. Treatment of waste by waste category, hazardousness and waste management operations [WWW Document]. URL. https://ec.europa.eu/eurostat/databrowser/view/ENV_WASTRT/default/table?lang=en.

Faraca, G., Astrup, T., 2019. Plastic waste from recycling centres: characterisation and evaluation of plastic recyclability. Waste Manag. 95, 388–398.

Fch, J.U., 2019. Fuel Cells and Hydrogen Joint Undertaking. Available from: ec. Eur. eu/research/fch (accessed 30.03. 10.).

Garðarsdóttir, S.Ó., Normann, F., Skagestad, R., Johnsson, F., 2018. Investment costs and CO2 reduction potential of carbon capture from industrial plants–A Swedish case study. Int. J. Greenh. Gas Control 76, 111–124.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782.

Hasan, M.M.F., Rossi, L.M., Debecker, D.P., Leonard, K.C., Li, Z., Makhubela, B.C.E., Zhao, C., Kleij, A., 2021. Can CO2 and renewable carbon Be primary resources for sustainable fuels and chemicals? ACS Sustain. Chem. Eng.

Icis, I.C.I.S., 2022. West EUROPEAN propylene capacity [WWW Document]. URL. https://www.icis.com/explore/resources/news/2009/12/07/9315714/european-chemical-profile-propylene/.

IEA, 2021. World Energy Outlook 2021.

Iea, I.E.A., 2022. Chemicals [WWW Document]. URL. https://www.iea.org/fuels-and-technologies/chemicals.

INEOS, 2022. Locations.

IRENA, 2021. Renewable Power Generation Costs in 2020 (Abu Dhabi).

Kagayama, M., Igarashi, M., Hasegawa, M., Fukuda, J., Kunii, D., 1980. Gasification of Solid Waste in Dual Fluidized-Bed Reactors. ACS Publications.

Kan, X., Hedenus, F., Reichenberg, L., 2020. The cost of a future low-carbon electricity system without nuclear power–the case of Sweden. Energy 195, 117015.

Kaza, S., Yao, L., Bhada-Tata, P., Van Woerden, F., 2018. What a Waste 2.0: a Global Snapshot of Solid Waste Management to 2050. World Bank Publications.

Kienzle, F., Andersson, G., 2009. A Greenfield Approach to the Future Supply of Multiple Energy Carriers. In: 2009 IEEE Power & Energy Society General Meeting. IEEE, pp. 1–8.

Larsson, A., Gunnarsson, I., Tengberg, F., 2018. The GoBiGas project-Demonstration of the production of biomethane from biomass via gasification. Göteborg Energi 10.

Lechtenböhmer, S., Nilsson, L.J., Åhman, M., Schneider, C., 2016. Decarbonising the energy intensive basic materials industry through electrification–Implications for future EU electricity demand. Energy 115, 1623–1631.

Maris, J., Bourdon, S., Brossard, J.-M., Cauret, L., Fontaine, L., Montembault, V., 2018. Mechanical recycling: compatibilization of mixed thermoplastic wastes. Polym. Degrad. Stabil. 147, 245–266.

Mazzoni, L., Almazrouei, M., Ghenai, C., Janajreh, I., 2017. A comparison of energy recovery from MSW through plasma gasification and entrained flow gasification. Energy Proc. 142, 3480–3485. https://doi.org/10.1016/j.egypro.2017.12.233.

(accessed 5.30.22) McKinsey, 2022. Helping build the circular economy for plastics [WWW Document]. URL https://www.mckinsey.com.br/industries/chemicals/ourinsights/plastics-recycling-using-an-economic-feasibility-lens-to-select-the-next-moves. .

Milios, L., Christensen, L.H., McKinnon, D., Christensen, C., Rasch, M.K., Eriksen, M.H., 2018. Plastic recycling in the Nordics: a value chain market analysis. Waste Manag. 76, 180–189.

Nemmour, A., Inayat, A., Janajreh, I., Ghenai, C., 2022. New performance correlations of municipal solid waste gasification for sustainable syngas fuel production. Biomass Convers. Biorefinery. https://doi.org/10.1007/s13399-021-02237-8.

OECD iLibrary, 2022. Global plastics outlook [WWW Document]. URL. https://www.oecd-ilibrary.org/environment/data/global-plastic-outlook.

Panepinto, D., Tedesco, V., Brizio, E., Genon, G., 2015. Environmental performances and energy efficiency for MSW gasification treatment. Waste and Biomass Valorization 6, 123–135.

Panepinto, D., Zanetti, M., 2021. Technical and environmental comparison among different municipal solid waste management scenarios. Sustainability 13, 3167.

Petrochemicals Europe, an I.S. of C., 2022. Cracker capacity [WWW Document]. URL. https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/.

Pineda, S., Morales, J.M., 2018. Chronological time-period clustering for optimal capacity expansion planning with storage. IEEE Trans. Power Syst. 33, 7162–7170.

Pissot, S., Berdugo Vilches, T., Thunman, H., Seemann, M., 2020. Dual fluidized bed gasification configurations for carbon recovery from biomass. Energy Fuel. 34, 16187–16200.

PlasticsEurope, E., 2020. Plastics—The Facts 2020. An Analysis of European Plastics Production, Demand and Waste Data. Plast. Eur., Brussels, Belgium.

Porshnov, D., 2022. Evolution of pyrolysis and gasification as waste to energy tools for low carbon economy. Wiley Interdiscip. Rev. Energy Environ. 11, e421.

Roussanaly, S., Ouassou, J.A., Anantharaman, R., Haaf, M., 2020. Impact of uncertainties on the design and cost of CCS from a waste-to-energy plant. Front. Energy Res. 8, 17.

Sepulveda, N.A., Jenkins, J.D., de Sisternes, F.J., Lester, R.K., 2018. The role of firm low-carbon electricity resources in deep decarbonization of power generation. Joule 2, 2403–2420.

Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., Paltsev, S., 2021. The cost of CO2 transport and storage in global integrated assessment modeling. Int. J. Greenh. Gas Control 109, 103367.

Soni, V.K., Singh, G., Vijayan, B.K., Chopra, A., Kapur, G.S., Ramakumar, S.S.V., 2021. Thermochemical recycling of waste plastics by pyrolysis: a review. Energy Fuel. 35, 12763–12808.

Stengler, E., 2019. Waste-to-Energy roadmap towards 2035. URL https//www. vivis. de/wp-content/uploads/WM9/2019_WM_001-014-Stengler. pdf.

Thunman, H., Vilches, T.B., Seemann, M., Maric, J., Vela, I.C., Pissot, S., Nguyen, H.N.T., 2019. Circular use of plastics-transformation of existing petrochemical clusters into thermochemical recycling plants with 100% plastics recovery. Sustain. Mater. Technol. 22, e00124.

[WWW Document]. URL UNFCC, 2015. The Paris agreement (accessed 5.30.22). https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

Valkenburg, C., Gerber, M., Walton, C., Jones, S., Thompson, B., Stevens, D., 2008. Municipal solid waste (MSW) to liquid fuels synthesis. Availability of Feedstock and Technology ume 1 (1), 1–43.

van der Meulen, S., Grijspaardt, T., Mars, W., van der Geest, W., Roest-Crollius, A., Kiel, J., 2020. Cost Figures for freight transport – final report. Res. to Prog. 1–85.

Vela, I.C., 2022. Carbon Materials: towards a Circular Economy through Thermochemical Recycling of Mixed Waste.

Vilella, M., 2019. Waste-to-energy is not a sustainable business the EU says. Zerowaste Eur.

Walter, V., Göransson, L., Taljegård, M., Öberg, S., Odenberger, M., 2022. Low-cost Hydrogen in the Future European Electricity System – Enabled by Flexibility in Time and Space. submitted to Applied Energy.

Warringa, G., 2021. Waste Incineration under the EU ETS-An Assessment of Climate Benefits.

Wei, M., McMillan, C.A., 2019. Electrification of industry: potential, challenges and outlook. Curr. Sustain. Energy Reports 6, 140–148.

Zep, 2011. The Costs of CO2 Capture: Post-demonstration CCS in the EU. Zero Emiss. Platf., Brussels, Belgium.