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Modelling of decarbonisation transition in national integrated energy system with hourly operational resolution

Manuel Sánchez Diéguez[a,*], Amirhossein Fattahi[a], Jos Sijm[b], Germán Morales España[b], André Faaij[a,b]

[a] University of Groningen, Groningen, Netherlands
[b] TNO Energy Transition

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ABSTRACT

In this paper, we present an optimisation integrated energy system model (IESA-Opt) for the Netherlands with the use of a linear programming formulation. This state-of-the-art model represents a scientific contribution as it integrates a European power-system model with a complete sectoral representation of the energy system technologies and infrastructure that account for all greenhouse gas emissions considered in the targets, and takes into consideration a detailed description of the cross-sectoral flexibility (e.g. flexible heat and power cogeneration, demand shedding from power-to-X and electrified industrial processes, short- and long-term storage of diverse energy carriers, smart charging and vehicle-to-grid for electric vehicles, and passive storage of ambience heat for the built environment). This model provides a detailed description of the operation of technologies and considers exogenous technological learning to simultaneously solve multi-year planning of investments, retrofitting, and economical decommissioning with intra-year operational, flexible, and despatch decisions. The model is applied to a case study of the Netherlands energy transition under the current climate policy and conservative projections for the economy and availability of resources. The results present a significant reliance on renewable energy sources, such as wind (800 PJ) and solar (300 PJ), to fuel the electrification revolution as well as biomass (550 PJ) for feedstock and heat purposes coupled with carbon capture, utilisation, and storage (CCUS) to achieve negative emissions in certain sectors. However, oil (880 PJ) and gas (1050 PJ) constitute almost half of the final energy demand as they are required for heat applications, industrial feedstock, refined oil products for export, and international transport fuel. Four different sensitivity analyses are presented for the emission reduction target, oil demand streams, biomass availability, and demand volumes. The most significant findings are as follows: 1) it is crucial to have simultaneous highly available biomass and CCUS storage capacities to achieve negative emissions and facilitate the transition; 2) even in a highly decarbonised scenario, it is necessary to simultaneously develop climate policies focused on international transport emissions, oil-based feedstock, and refined-oil product exports to completely displace oil from the energy mix; 3) (imported) biomass has the ability to decrease system costs (3% under conservative scenarios of availability and price); however, for biomass prices higher than 20 €/GJ, this effect is lower; 4) in relative terms, the system is most sensitive to demand uncertainties from the transport sector than any other sector, followed closely by the industrial sector.

Abbreviations: A+ A–G, Different residential energy efficiency labels where G is the least efficient and A+ the most efficient; ABM, Agent-based model; BU, Bottom-up; CAES, Compressed air energy storage; CCUS, Carbon capture, utilisation, and storage; CHP, Combined heat and power; CO2, Carbon dioxide; CNG, Compressed natural gas; CTL, Clustered technological learning; DAC, Direct air capture; DSM, Demand-side management; ESM, Energy system model; ETS, Emission trading scheme (European); EU, European Union; EV, Electric vehicle; GHG, Greenhouse gas; GIS, Geographical information system; GTS, Gasunie Transport Service; HD pipeline, High-density pipeline; HDV, Heavy-duty vehicle; HT heat, High-temperature heat; HTR, Hourly temporal resolution; HV grid, High-voltage grid; IEM, Integrated energy model; LD pipeline, Low-density pipeline; LDV, Light-duty vehicle; LV grid, Low-voltage grid; LP, Linear programming; LT heat, Low-temperature heat; LULUCF, Land use, land-use change, and forestry; MACC, Marginal abatement cost curve; MD pipeline, Medium-density pipeline; MRL, Multi-regional learning; MV grid, Medium-voltage grid; MIP, Mixed-integer programming; NECP, National energy and climate plan; OBP, Oil-based Products; OESM, Optimisation energy system model; OPF, Optimal power flow; P2Heat, Power to heat; P2Hydrogen, Power to hydrogen; P2Gas, Power to natural gas; P-to-L, P2L, Power to liquids; P2Mobility, Power to mobility; PBL, Netherlands Environmental Assessment Agency; PHES, Pumped hydro-energy storage; SHT heat, Super-high-temperature heat; SSAS, Solid state ammonia synthesis; SSP, Shared socioeconomic pathway; TD, Top-down; TES, Thermal-energy storage; TNO, Netherlands Organisation for Applied Scientific Research; UoC, Units of capacity; V-to-G, V2G, Vehicle to grid; VOLL, Value of lost load; VRES, Variable renewable energy sources.

[*] Corresponding author.

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Nomenclature of the model

Indexes

Symbol	Description
p	Index of the set conformed by all the modelled periods
h	Index of the set conformed by all the hours in a year
d	Index of the set conformed by all the days in a year
a	Index of the activities set
ae	Index electricity related activities subset, A^e
ah	Index of the national heat related activities subset, A^h
ag	Index of the gas related activities subset, A^g
$t, \mathrm{t}_i,\ t_j$	Indexes of the technologies set
te	Index of the technologies representing air released emissions in the considered target scope.
td	Index of the dispatchable technologies subset
tp	Index of the operation technologies subset
tf	Index of the flexible technologies subset
tf_b	Index of the flexible technologies of the battery type subset
tc	Index of the flexible CHP technologies subset
ts	Index of the shedding technologies subset
ti	Index of the infrastructure technologies subset

Parameters

Symbol	Description
$VC_{t,p}$	The variable cost of a technology in a period
α_t	Annuity factor of a technology (or in this case the inverse)
$IC_{t,p}$	Investment cost of a technology in a period
DF_t	Fraction of the capital cost of a technology that remains after premature decom
$RC_{\mathrm{t}_i,t_j,p}$	Retrofitting cost from one technology to another
$FC_{t,p}$	Fixed operational cost of a technology in a period
$AP_{t,a,p}$	Activities inputs and outputs profile of a technology
$V_{a,p}$	Exogenous required activity volumes in a period
Γ_t	Available use of a technology per unit of capacity
E_p	Absolute CO_2 emission target in a certain period.
RM_{t_i,t_j}	Binary matrix specifying which technologies can be retrofitted into others
$S^{min}{}_{t,p},\ S^{max}{}_{t,p}$	Minimum and maximum allowed installed capacities of a technology in a year
$P_{h,tp}$	Hourly availability or reference operational profile of a technology
$AE_{t,a}$	Binary parameter indicating the hourly electricity activities of a technology
$R^{dw}_{td,p},\ R^{up}_{td,p}$	Ramping up and down limits of hourly dispatchable technologies
η_{tc}	Only-heat reference efficiency of a flexible CHP
ε_{tc}	Only-power reference efficiency of a flexible CHP
SC_{ts}	Power shedding of a technology per unit of capacity
$UtP_{ts,p}$	Use-to-power ratio of a shedding technology in a period
SF_{ts}	Maximum allowed shedding fraction of a shedding technology
$AG_{tf,a}$	Binary parameter indicating the gas activities of a technology
FC_{tf}	Flexibility capacity in terms of the impact on the corresponding network of a technology.
NN_{tf}	Non-negotiable load of flexible technologies.
CC_{tf}	Charging (or discharging) capacity of a storage technology.
CT_{tf}	Charging time of a storage technology.
VU_{tf}	Hourly profile of the usage of a flexible vehicle (not connected to the grid).
AS_{tf}	Average speed of a flexible vehicle.

Variables

Symbol	Description
$u_{t,p}$	Use of a technology in a period
$i_{t,p}$	Investments in a technology in a period
$d^{pre}{}_{t,p}$	Premature decommissioning of a technology in a period
$r_{t^i,t^j,p}$	Retrofitting from one technology to another in a period
$s_{t,p}$	Stock (installed capacity) of a technology in a period
$d^{cum}{}_{t,p}$	Cumulative decommissioning of a technology in a period
$d^{lt}{}_{t,p}$	Decommissioning of a technology in a period due to lifetime expiry
$u_{h,td,p}$	Hourly use of a dispatchable technology in a period
$\Delta q^{up}{}_{h,tf,p}$	Increase in electricity demand from a flexible technology in an hour in a period
$\Delta q^{dw}{}_{h,tf,p}$	Decrease in electricity demand from a flexible technology in an hour in a period
$\Delta u_{h,tc,p}$	Deviation in use of a flexible CHP technology in an hour in a period
$\Delta p_{h,tc,p}$	Deviation in power output of a CHP technology in an hour in a period
$\Delta u_{h,ts,p}$	Decrease in use of a shedding technology in an hour in a period
$l_{h,tf,p}$	Losses from deviations in use of flexible technologies in an hour in a period
$\Delta q^{max}{}_{h,tf,p}$	Maximum increase limit of power demand of a flexible technology in an hour
$\Delta q^{min}{}_{h,tf,p}$	Maximum decrease limit of power demand of a flexible technology in an hour
$\upsilon^{max}{}_{h,tf,p}$	Upper saturation limit from shifted volume in an hour in a period
$\upsilon^{min}{}_{h,tf,p}$	Lower saturation limit from shifted volume in an hour in a period
$u_{d,td,p}$	Daily use of a dispatchable technology in a period
$\Delta q^{up}{}_{d,tg,p}$	Upwards deviation in use of a daily storage technology in a period
$\Delta q^{dw}{}_{d,tg,p}$	Downwards deviation in use of a daily storage technology in a period

1. Introduction

Following the EU 2030 Climate and Energy Framework [1], the Netherlands is required to reduce its greenhouse gas (GHG) emissions by 49% by 2030, compared to its 1990 levels, and realise a 95% reduction by 2050[1] [2]. The overall focus of the Dutch energy transition pathway in the coming decades is towards decarbonisation, energy efficiency, and system integration [3], notably through the increase in renewable electricity production and the conversion of 'green electrons' into 'green molecules' [4]. Higher levels of electrification in various sectors increases the need for further sector coupling and system integration. The use of this highly electrified energy system, which is mainly supplied by variable renewable energy sources (VRES), results in a greater need for flexibility in the energy system as a whole and the power system in

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E-mail address: m.sanchez.dieguez@rug.nl (M. Sánchez Diéguez).

[1] The GHG-emission reduction objectives are often reviewed by the European Commission and national governments; therefore, in this study, we use the official intentions of the Dutch government until January 2021. However, the targets are likely to become more stringent in the upcoming years.

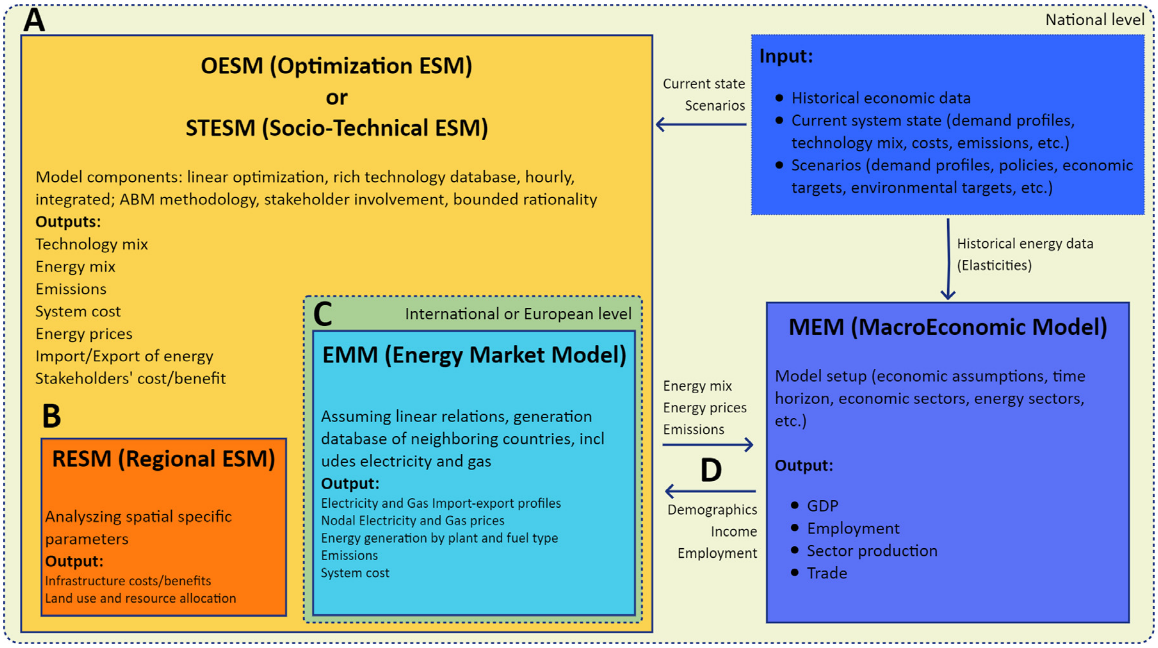

Fig. 1. Optimisation integrated ESM (IESA) framework presented by Fattahi et al. [6].

particular [5]. However, it should be noted that the future layout of the energy system and energy mix is still uncertain, and complex methodologies are required to evaluate its possibilities.

One of the most accepted methods of analysing the transition towards the described energy system requires the application of high-resolution energy system models (ESMs) for addressing the implications of VRES on the energy system. For instance, optimisation ESMs have been extensively used in the energy modelling community; however, they have their respective shortcomings. With a focus on national models that consider all the energy sectors and GHG emissions, Fattahi et al. proposed a list of capabilities required by ESMs to address the challenges raised by the increasing share of VRES, and the resulting complexity and required system integration [6]. They synthesised the challenges into six categories, intermittency and flexibility, further electrification, new technologies and technological change, decentralisation, human behaviour, and macroeconomic interactions, and proposed a conceptual framework for addressing them, as presented in Fig. 1. For European countries, such as Germany and the Netherlands, this framework is built around a central national ESM containing or linked to a European energy-market model and can be easily linked with a regional model.

Fattahi et al. [6] also performed a broad multi-criteria analysis (Appendix A) over an extensive literature review of existing ESMs, highlighting the need for an improved modelling approach. amongst these ESMs, there is currently no model that simultaneously includes the following essential capabilities for addressing the aforementioned challenges: hourly temporal resolution, European power despatch, multi-period investment optimisation, complete representation of the energy system with an accounting of the GHG emissions included in the climate policy targets, complete technological representation of activities within each sector while taking into consideration (exogenous) efficiency improvements and (exogenous) technological learning, and an appropriate account of the costs of the infrastructure transformation. Some of these capabilities, such as the consideration of a number of periods, interconnection within the European power system, or flexibility and infrastructure representations, can have a major impact on the modelling outcome, as presented in [7]. Furthermore, it should be easily possible to integrate the model with other tools to provide linked approaches for addressing the energy transition complexities from broad and synchronised perspectives.

For example, the integrated MARKAL–EFOM1 (market-allocation–energy-flow-optimization-model) system (TIMES) model [8] provides a detailed techno-economic representation of all the energy sectors, sector coupling technologies, and infrastructural limitations, while using ‘integral’[2] time slices instead of an hourly temporal resolution. The use of aggregated time slices is an overestimation of the potential contribution of large base-load power plants and underestimation of the need for supply–demand management and storage with high shares of VRES [9]. In a manner similar to TIMES, OPERA provides a detailed techno-economic representation of the energy system [10]; however, it lacks optimal multi-year investment decisions [11]. Neglecting the multi-year optimisation undervalues the role of the current technological stock and its techno-economic lifetime on the system costs. Python for power system analysis (PyPSA) provides an open-access ESM that emphasises power-network details such as the physics of power flow according to the impedances in the network [12] at the expense of a simpler technological representation of other sectors. It has been communicated on the PyPSA-Eur-Sec website that the model is being expanded to take into account all the emissions considered in the targets. Nevertheless, on top of it being not published yet, its representation of non-power sectors is being simplified and does comprise perfect foresight for planning nor endogenous investments in industrial processes.[3] Similarly, COMPETES provides a detailed representation of the European power-sector dynamics for operation and planning decisions, and it is well suited to flexible demand technologies [13]. However, it is focused on the power system and does not include all sectors and activities related to the decarbonisation targets. Compared to other ESMs, OseMOSYS requires less time for computation and no upfront financial investment as it is an open source modelling system; however, it does not account for high technological

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[2] Approximate the (residual) load duration curve by dividing a year into a limited number of time slices (typically 4–12) to represent seasonal, daily, and diurnal variations in demand and supply [84].

[3] We are looking forward to the updated release, as we are certain that when PyPSA-Eur-Sec is further developed to the ambitions mentioned in their website, a great opportunity to make a collaborative use of both models will arise.

Table 1
Modelling capabilities of reviewed ESMs.

Model	Modelling Capabilities						
	Hourly resolution	European power despatch	Multi-year investment optimisation	Complete energy system representation	High technological resolution	Infrastructure representation	Accessibility
TIMES [8]		Y	Y	Y	Y	Y	Medium
OPERA [11]				Y	Y	Y	Medium
COMPETES [13]	Y	Y	Y		Y	Y	Low
PyPSA [12]	Y	Y				Y	High
OseMOSYS [14]		Y	Y				High
REMix [16]	Y	Y	Y			Y	Low
IESA-Opt	Y	Y	Y	Y	Y	Y	High

resolution and infrastructure constraints [14]. REMix uses the EnDAT tool [15] to pre-process the heat and power-demand data for incorporating geospatial variations in the hourly optimisation model [16], but the model and its database are not publicly accessible to this date, and many sectoral activities are excluded from the scope of the model. As indicated in Table 1, none of these models has all the capabilities required to address the aforementioned modelling challenges. Therefore, the development of a new model that simultaneously satisfies all these capability requirements is necessary.

This study presents a new model called the integrated energy system analysis optimisation (IESA-Opt) model, which facilitates the harmonised and combined use of (future) simulation, regional, and macroeconomic-focused analyses as part of the IESA modelling framework for the Netherlands. This linear programming (LP) model simultaneously provides all the capabilities listed in Table 1, as it can solve the short-term hourly operation and long-term 5-year-interval planning problem from 2020 to 2050 (with the possibility of extending the time horizon). Furthermore, the model includes multi-year techno-economic data of more than 700 technologies in all sectors for both energy transformations (i.e. electricity, refineries, heat, hydrogen, gas, and biomass) and final demand (i.e. residential, services, agriculture, transport, and industry). In this rich technological representation, cross-sectoral technologies are included, such as P2Heat, P2Gas, P2Hydrogen, P2Liquids, P2Mobility, and V2Grid, as well as the corresponding descriptions of their flexible hourly operation. Exogenous technological learning, efficiency improvements, and decommissioning and retrofitting parameters are also included in the formulation. To model the implications of hourly import and export of electricity on the Dutch energy system, IESA-Opt comprises an hourly electricity despatch of EU countries with 20 nodes, each with their own hourly load, specific hydro storage capacity, onshore wind, offshore wind, and solar profiles. In addition to GHG emissions related to the energy system (divided into emissions within and outside the emission trading scheme (ETS)), the model also takes into consideration the emissions from non-energy sources, such as enteric fermentation, fertilisers, manure management, and refrigeration fluids. To address the network buffer capacity, IESA-Opt represents the operation of gaseous networks [17] based on a daily balance despatch [18]. The energy infrastructure is modelled in ten networks for different voltage levels of electricity and different pressure levels of natural gas, hydrogen, and CCUS, as well as for the distribution of district heating.

One of the objectives of developing IESA-Opt is to provide a low entry barrier (i.e. transparent) model that requires no upfront financial investment (to purchase specialised licenses) for academic research. In addition, owing to the enormous size of the optimisation problem, there is a need for efficient computing software that is commercially available. Therefore, two commercial software packages with a free academic license are selected to maximise the computational efficiency and accessibility of the model. IESA-Opt is implemented in the commercial AIMMS software [19], which uses an algebraic modelling language, such as GAMS, AMPL, and MPL. The GUROBI mathematical optimisation solver [20] is used to solve the LP problem in parallel central processing unit cores.[4] Moreover, to expand the accessibility of the model and its results, the results of the model are visualised using a web-based user interface that is realised in the R programming language [21]. The model's source code and its database are available online through the model's web user interface[5] [22].

The main research objective of this study is to develop a method of analysing the impact of cross-sectoral flexibility in an integrated energy system of the Netherlands to accommodate large amounts of variable renewable electricity. The method of transitioning the energy system for taking into consideration the interactions of energy usage, emissions, and costs also needs to be determined. To better explain these objectives, the main contributions of this study are presented as follows:

- It presents a multi-sector ESM that simultaneously considers hourly power dynamics, integrates the European power despatch, uses multi-year optimisation, includes all sectors of the energy system with a complete emissions inventory, adopts a rich technological description, and represents system infrastructure costs and potentials.
- It applies the IESA-Opt model in an optimisation case study of the Netherlands energy transition and presents and analyses the results after making use of the aforementioned modelling capabilities, such as exogenous technological learning; hourly despatch of the European power system, investment, retrofitting, and economic decommissioning decisions; cross-sectoral flexibility dynamics; gaseous infrastructure network flows and seasonality; and a complete inventory of GHG emissions in the system.
- It uses the practical modelling framework to perform sensitivity analyses to understand the implications of biomass and CCUS in achieving negative emissions; explores the roles of the various demand streams for oil; analyses the impact of biomass availability and its cost in the transition; and quantifies the uncertainty of key demand volumes for different sectors.

In addition to scientific contributions, this work provides a transparent and accessible modelling framework that can be adopted by different audiences for diverse purposes. The model code and database are open access and are available online. Owing to this and the modular structure of the model, it is suitable for diverse transdisciplinary applications (such as macroeconomic, behavioural, or regional analyses), and it is built such that, by simply modifying the database, the model can be used to study other countries or systems of interest. These features make the model ideal not only for its purpose within the IESA framework, but also for integration with any other framework in the academic community.

The remainder of this paper is organised as follows. In Section 2, we provide an overview of the IESA-Opt formulation and introduce the scenario used for the case study. Section 3 describes the key results of the

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[4] https://www.gurobi.com/resource/parallelism-linear-mixed-integer-programming/

[5] https://www.energy.nl/iesa. This paper describes version 3.06 of IESA-Opt. Please note the version number for accessing the model's web portal.

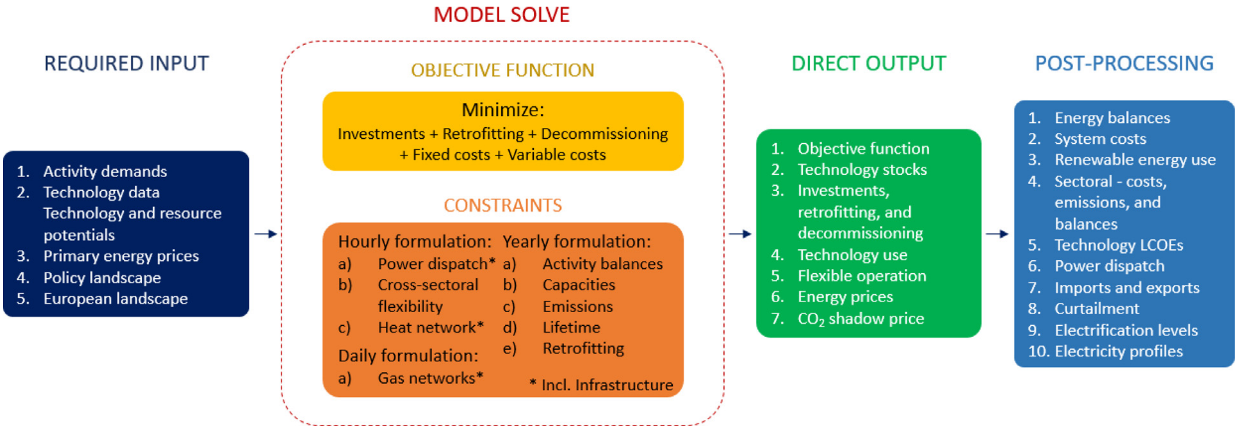

Fig. 2. Methodological elements in the IESA-Opt framework.

scenario analysis, which is followed by a sensitivity analysis presented in Section 0. After the conclusion presented in Section 0, supplementary materials are presented in Appendices A–G.

2. Methodological approach

To provide an analysis of the Netherlands energy transition while considering the operational impact of VRES and cross-sectoral flexibility amongst the integrated energy sectors, this study presents the IESA-Opt model and illustrates its capabilities using the case study of the energy transition in the Netherlands. This section presents the methodological foundations of the IESA-Opt model and the general scenario used for the case study. Further details regarding the model methodology can be found on the model website.

2.1. IESA-Opt framework

To better present the framework, we divide it into two main components: the optimisation process and the energy system representation.

2.1.1. Optimisation process

The IESA-Opt model provides a cost-optimal system configuration and optimal technology usage for the energy-system transition of the Netherlands. As indicated in Fig. 2, six input elements are required: the demands of the various activities based on macroeconomic projections, such as the number of houses or tons of steel required; the expected costs and operational parameters of the technologies that can meet the demand of the various activities; the technology and resource potentials; the price forecasts for the primary energy resources fuelling all theenergy transformation activities; the policy landscape assumed for the energy system comprising technology restrictions and emission reduction targets; and the European landscape, including the ETS carbon price and installed capacities of the generators in the 20 European Union (EU) nodes (excluding the Netherlands).

In addition, Fig. 2 shows that, subsequent to the execution of the scenario run, the model provides direct results, such as the objective function value (i.e. total costs of the decisions of the entire system), the technological stocks (installed capacities) for the entire multi-year transition period; the investments,[6] retrofitting, and premature decommissioning required to achieve such an optimal configuration; the (hourly) use of the technologies present in the system and their flexible operation deviations; the energy prices resulting from the endogenous energy transformation (e.g. electricity and hydrogen production); and the CO_2 shadow price resulting from imposing the emission cap. However, from these direct results, several other results can be obtained in a post-processing phase. The latter makes IESA-Opt ideal for describing various characteristics of the optimal energy transition, such as energy balances, renewable energy use, system and sectoral costs and emissions, levelized costs of electricity (LCOEs) of the technologies (after operation), visualisations of the hourly power despatch, imports and exports of various energy carriers, curtailment of intermittent renewable-energy sources, level of electrification, and electricity profiles after flexibility is applied. It is important to highlight that the ability to simultaneously account for intra-year behaviour (i.e. hourly and daily dynamics) and multi-year capacity planning under perfect foresight for all the interlinked sectors of the energy system makes IESA-Opt a state-of-the-art tool for analysing the real costs of adopting VRES to achieve system decarbonisation.

In order to realise these results, IESA-Opt has being designed as a LP formulation that minimises the cost of investments, retrofitting, decommissioning, and operation. Its detailed formulation is presented in Appendix C. However, we present a conceptual description of the constraints used in the model. The optimisation problem is subject to a set of constraints used to describe the feasible transition and operation ranges of all the technologies. We separated the constraints into three main categories based on their temporal resolution: yearly, daily, and hourly.

The yearly constraints comprise five constraint clusters with the following objectives: 1) to ensure that all driver activities (exogenous demand) are satisfied and all the endogenous energy activities are balanced; 2) to ensure that the use of technologies does not exceed the capacity and national potentials; 3) to impose the maximum lifetime of technologies; 4) to indicate which technologies might be transformed into another new technology (retrofitting); and 4) to enforce the GHG reduction target.[7]

The daily constraints are focused on the feasibility of operation of the gaseous pipelines, namely, all the operating pressures of natural gas and hydrogen networks, as well as the transport of captured CO_2

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[6] Investments are represented in the objective function while taking into consideration both the discount rate and economic lifetime merged into an annuity factor used to annualise the investments for each period. Both the objective function and multi-period formulations for the accounting of technological stocks and technical lifetimes are presented in Appendix B.

[7] It is important to mention that approximately 85% of the emissions considered within the 2017 national inventory of the Netherlands [47] is accounted for by the activities included in the energy-system framework, and for the remaining 15% (primarily agricultural activities), a less-detailed approach is used. Here, the emissions resulting from activities such as enteric fermentation, manure management, and the use of fertilisers and refrigeration fluids are input into the model as driving activities, and their potential reductions and costs are addressed via marginal abatement cost curves (extracted from the IMAGE model database [41]). A complete description of the methodology is provided in Appendix D.

(CCUS network). A daily balance is sufficient to capture the dynamics of gaseous networks, mainly owing to the buffer effect (line pack) of networks (where the hourly balance is not zero) [17]. The objective of using the daily resolution is to address seasonality, buffer opportunities, and infrastructure costs. To achieve this, two main constraints are implemented: the first one enforces a strict daily balance in the gaseous networks, which means that energy inputs and outputs must match daily, and the second one sets a cap for the daily transit of energy in a network in line with the available infrastructure. With this representation, the model dispatches national wells and imports, manages the daily operation of the buffers (e.g. gas storage chambers), and describes other generation processes with particular sectoral dynamics, such as fermentation, (bio)gasification, and electrolysers (which are also ruled by hourly constraints). In addition to the despatch, in this formulation, the costs of required network expansions (e.g. investments in grid developments to transport hydrogen or captured CO_2) are taken into consideration.

The last category, corresponding to the hourly constraints, presents the heaviest mathematical burden for the optimisation problem and comprises the optimal despatch for the power system. Modelling the power despatch within ESMs demands that choices be made to avoid enormous computational requirements. Poncelet et al. [23] demonstrated that poor temporal resolution negatively affects the reliability of analyses with a moderate or high presence of VRES and recommended the use of hourly resolution as a priority. They also concluded that the adoption of a sequential description of the power despatch maintains the chronological order in the variability of the events, which is crucial for short- and long-term storage technologies. The same study highlighted the importance of unit commitment, which is used to describe start-up and shutdown times as well as minimum downtimes. This type of description of the power system requires the use of integer variables, which would turn the problem formulation into a mixed integer program (MIP). However, in the same study, it was stated that unit commitment loses relevance after a certain level of VRES penetration, owing to the presence of fewer thermal units in the system. This observation is further reinforced by another study, which states that MIP unit commitment performs better in studies with a low presence of VRES, but for high levels of VRES, an LP approach suffices for providing reliable results [24]. Similarly, there is plenty of evidence that an increase in the geographical scope of the model to take into consideration European cross-border interactions has a significant impact on the outcome reliability of the models [25]. Based on this, an LP model is proposed in this paper, and an hourly resolution is adopted with the sequential power despatch of the entire interconnected European electricity network, in addition to different voltage levels for the Netherlands and 20 EU interconnected nodes, as shown in Fig. 3 and presented in Appendix E.

In a manner similar to the gaseous networks, this formulation accounts for the required investments in infrastructure expansions to transport and transform electricity amongst the three low-, mid-, and high-voltage lines considered. It also accounts for the investments required to increase the interconnectivity of the Netherlands with offshore windfarms and the surrounding countries. These infrastructure descriptions are presented with an hourly resolution for electricity.[8]

The cross-sectoral flexibility is also described with an hourly resolution and is tailored to describe three types of modelled flexibility archetypes: combined heat and power (CHP), demand shedding, and conservational flexibility (which includes load shifting, storage, passive storage, smart charging, and vehicle-to-grid behaviours). CHPs provide flexibility in two dimensions: 1) by modifying their fuel input, and 2) by changing their heat-to-power ratio within a possible deviation range from a reference operation profile [26]. Demand shedding curtails the demand for electricity from a reference operation profile. This form of flexibility allows the system to overinvest in capacity [27] to allow a decrease in operation for hours when electricity is scarce and prices are high [28]. This flexibility form can be applied to various processes such as the production of heat [29], hydrogen [30], methanol [31], methane [32], hydrocarbons [33], chlorine [34], ammonia [35], and other chemicals [28]. In the case of load shifting, the system does not curtail but reallocates the energy demand by increasing and decreasing it at different hours (always within a feasible operating range). This conservational flexibility is modelled using three constraints: the balancing constraint, where the increases in energy demand over a certain time period must be equal to the decreases in electricity demand in another time period (plus the generated efficiency losses) inside a feasible rescheduling window; the capacity constraint, which states the upward and downward limits between which rescheduling can occur; and the saturation constraint, which states how much energy can be rescheduled inside a feasible rescheduling window. All demand responses [36], storage [37], passive storage [38], smart charging, and vehicle-to-grid transactions [39] fall within this flexibility archetype and are characterised by their own specific balancing, capacity, and saturation constraints.

2.1.2. Energy system representation

For each type of energy-system modelling, it is important to know what is included within the boundaries of the energy system under consideration. In IESA-Opt, the energy system is defined by activities and technologies, where the former refers to products and drivers in the economy and the latter refers to the different paths in which the model satisfies those activities (analogous to the commodities and processes nomenclature in TIMES [40]). Appendix B presents a complete list of activities and technologies of the system.

Conceptually, there are four types of activities: driver activities, energy activities, primary energies, and emissions. Fig. 4 presents the specific activities that can be included within each type. Driver activities (final activities) comprise those corresponding to the five main sectors of the energy system (residential, services, agriculture, industry, and transport) along with the emission sources that are not fully contained in the energy system and the electricity demand of the 20 interconnected EU countries. Their volumes (demands) are fed into the model exogenously according to macroeconomic drivers, such that the model can decide which technologies will be used to satisfy them. The use of these technologies determines the energy requirements (both primary and processed energy) and the directly emitted CO_2 equivalents. The processed energy demand resulting from the use of technologies satisfying the final activities must then be met by the supply of energy from the energy conversion sectors (energy activities), such as electricity generation and oil refining. Here, the model decides which technologies to invest in and use optimally in order to satisfy the endogenous demand of energy at a lower social cost, thus resulting in primary energy requirements and related GHG emissions.

This energy system representation, wherein the non-energy-related emissions are included by means of their marginal abatement cost curves (MACCs) [41], allows for a complete description of the energy-related costs and a complete account of the emissions considered within the national targets.

2.2. Scenario definition

As mentioned in the previous section, the definition of a reference scenario in IESA-Opt includes six definitions of the required inputs, namely, the projected demand of driving activities, cost of input resources (primary energy costs), potential for decarbonisation technologies, policy regulations assumed for the transition, projected costs and operational parameters of the technologies, and assumed EU power system capacities (Fig. 5). In this section, the sources and definitions of the storylines for each of these definitions are outlined briefly, while the explicit parameters used for this case study are reported in Appendix F.

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[8] Analogous to the case of electricity, the district heating network is also described at an hourly scale to represent the dispatch, storage, infrastructure capacities, and infrastructure expansions.

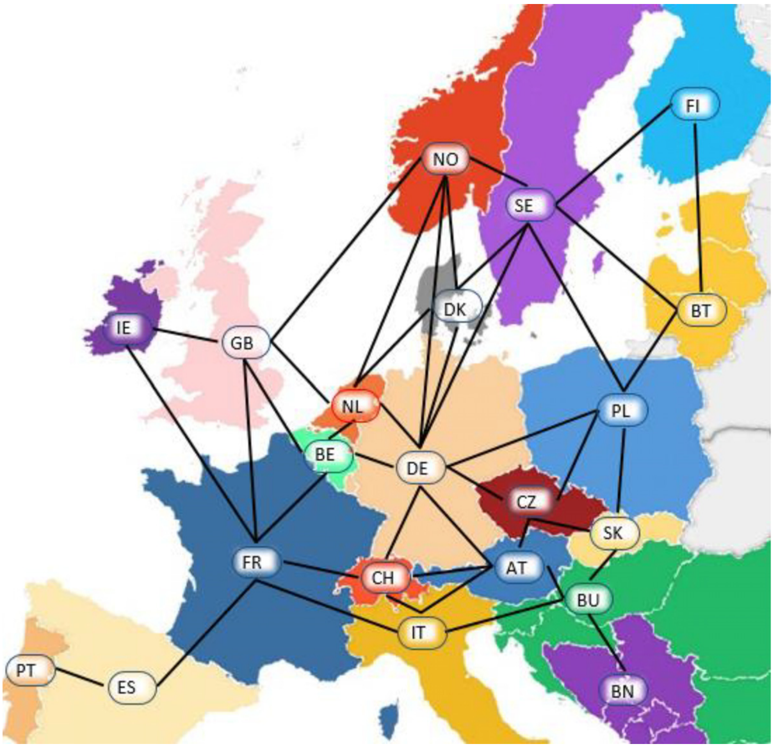

Fig. 3. Nodal representation of the European power system considered in IESA-Opt.

For the first two types of activities, the projected demand of the driver activities and part of the resources' costs are extracted from JRC's POTEnCIA Central Scenario for the Netherlands [42], which was adapted in line with the GDP growth rates presented in the 2018 Ageing Report [43]. These projections imply a business-as-usual economic development, which falls within the narrative of the second shared socioeconomic pathway[9] (SSP2) [44]. Biomass costs were extracted from the reference case of the ENSPRESO database [45] as well as the majority of the considered potential renewable technologies in the Netherlands, which also corresponds to their reference estimations (moderate potential).

The environmental policy landscape of the Netherlands is presented by the Dutch government in the National Energy and Climate Plan [46] and includes climate policy targets of 49% and 95% emission reductions for 2030 and 2050, respectively, compared with the 1990 levels.[10] This target includes emissions from energy use, industrial processes, agriculture, and waste management, which are required to completely account for the target in line with the data from the National Inventory on GHG emissions of the Netherlands [47].

This reference scenario for the Netherlands imposes two key constraints on nuclear and coal power generation. Although there is no explicit Dutch policy banning the use of nuclear power, there seem to be no plans in the short- or mid-term to further adopt it, and it will most probably disappear from the mix after 2033 [48]. For this reason and the apparent low social acceptance of nuclear power in the Netherlands, this reference scenario forbids the use of nuclear technologies after 2035. In addition, the Dutch Climate Agreement of 2019 prohibits the use of coal for power generation after 2030, although it is not yet clear if it will be allowed in combination with CCUS [49]. Therefore, coal power plants will not be allowed to run after 2030, but coal with CCUS is allowed in this scenario. In addition to these two constraints, the scenario considers no imposed social or policy constraints for the adoption of technologies, and thus, the model scenario output reflects a cost-optimal configuration based merely on technical restrictions.

Next, the technology-specific parameter set consists of the activity inflows and outflows for each technology (i.e. energy or commodity balance) and the cost profiles of the technologies (i.e. investment, and fixed and variable operational costs). Therefore, part of the scenario description requires projections of the cost and efficiency development of maturing technologies. This reference scenario comprises the gathered data from various central scenario descriptions of various sources. Most of the technologies described in IESA-Opt are based on the reference scenario of the ENSYSI model [50] wherein novel low-carbon technologies experience a maximum learning rate of 20%. The model also bases technology data projections of the transport sector on those from the POTEnCIA Central Scenario [42]. Moreover, the reference scenario uses data projections from the available technology sheets of the Netherlands Organisation for Applied Scientific Research (TNO) [51] for technologies such as power-to-liquid alternatives, electrolysers, and direct-air-capture units. The complete technology data assumptions for this scenario as well as the link to the sources may be referred to on the web portal of the model [22].

As IESA-Opt dispatches electricity for the whole of Europe, the climate targets of EU-member-state power systems influence the mix of generation assets of interconnected nodes (which is a key indirect input element of the scenario definition). Member states must adhere to the EU targets, but additional (voluntary) national policy measures and contributions may vary. Such a variety of responses could strongly influence the outcome of the model, as the level of discrepancy in national policies may raise price differences, thus resulting in highly imbalanced import and export flows. To address this issue, the reference scenario consid-

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[9] The five SSP scenarios used to produce IPCC assessment reports explore the way the world may change over this century under different storyline assumptions. The SSP2 storyline explores a future wherein moderate efforts are taken to mitigate climate change, primarily based on the adoption of basic climate policies and continuous uneven economic development among countries.

[10] Emissions in the Netherlands accounted for 222 Mton CO_2 eq. in 1990 excluding land use, land-use change, and forestry [47], which translates to a cap of 108 and 11 Mton CO_2 eq. for 2030 and 2050, respectively.

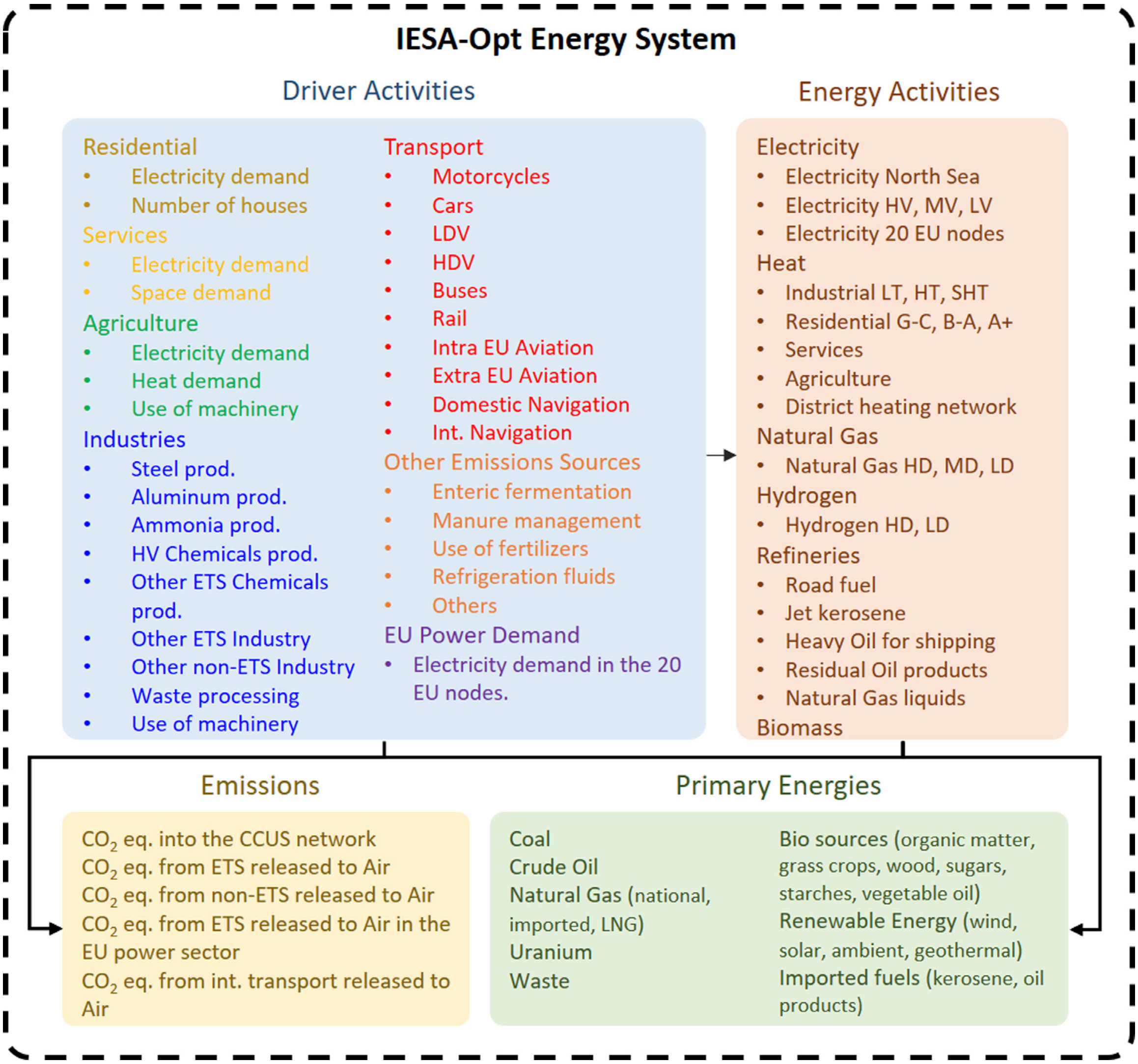

Fig. 4. Energy system representation of activities considered within the IESA-Opt framework.

ers EU generation assets from the mid-term adequacy forecast 2016 and the Sustainable Transition scenario runs until 2035 by the European Network of Transmission System Operators for Electricity [52] and is then complemented with updated data from the National Trends TYNDP scenario 2020 for the year 2040 [53]. Based on this configuration, we run a highly decarbonised capacity expansion plan for all European countries for the years 2040, 2045, and 2050 to ensure that the power generation assets of the Netherlands are aligned with those of other European countries. In this manner, we avoid highly unbalanced import and export situations due to modelling discrepancies for the years 2045 and 2050. The resulting European power system configuration used for this scenario is presented in Appendix G.

Sections 3 and 4 present the modelling results of the aforementioned case study. Section 3 presents the results of a single run using the model to explore the scenario described above. Section 4 presents deviations from the reference scenario in the form of sensitivity analyses to explore the following topics: 1) climate policy targets and the role of biomass and CCUS in achieving various objective levels; 2) the use of oil-based products (OBPs) neglected by current climate policy and how climate policy could be expanded to include them; 3) price and availability uncertainty of biomass in the system outcomes; and 4) uncertainty in demand volumes (activity levels) of the driver sectors of the economy.

3. Insights obtained from the reference scenario

In this section, we present the results of the reference scenario described in section 0. The results are split into seven subsections, each addressing one particularity of the energy transition or an advanced capability of the model. The first three subsections are focused on the energy mix, emissions, and transition costs. Subsection four describes the generalities of the resulting system configurations. The next subsection illustrates how the model represents the operation of the gas networks. Subsection six presents the particularities of the power sector in the resulting transition. Finally, the last subsection is focused on the role of cross-sectoral flexibility.

3.1. Energy mix

A crucial output element delivered by ESMs is the energy mix. Fig. 6 presents the energy mix for the Netherlands resulting from the optimisation of the reference scenario. This graph shows that the main transformation is, as expected, the substitution of fossil fuels with renewable energy sources. It should be noted that there is a significant reduction in the use of oil, which is mainly triggered by the substitution of fossil transport alternatives. It is important to mention that the use of coal is almost negligible in 2050, and it only remains in use in the steel sector in

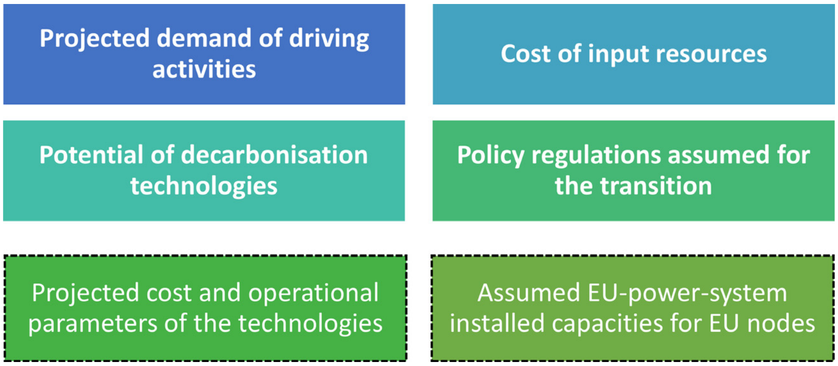

Fig. 5. Six required scenario definitions of IESA-Opt.

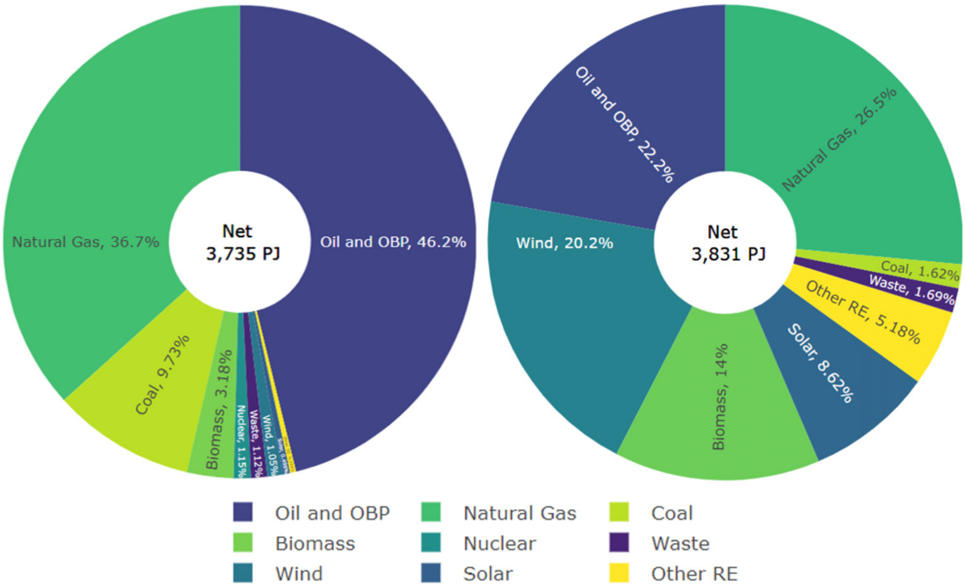

Fig. 6. Netherlands' primary energy mix in IESA-Opt (including international transport). Left: 2020. Right: 2050.

the form of a small amount of blast-furnace capacity with CCUS. In contrast, natural gas still comprises an important share of the mix, mainly because of its adoption as a shipping fuel and the emission window for non-ETS activities opened by the negative emissions of the biomass and CCUS coupling.

Furthermore, in addition to the considerable share of natural gas, the presence of oil and OBPs in the 2050 primary energy mix shows the way in which the current climate policies are insufficient for avoiding the use of fossil fuels. As shown in Fig. 7, most of the remaining uses of OBPs are outside the scope of the currently adopted climate policies in the Netherlands. This figure shows an increased use of kerosene for aviation and OBPs for industrial feedstock, while refineries are still being fuelled with oil (although they adopt CCUS). These three activities are neglected by the current adopted climate policy due to the following reasons: 1) there is no emission reduction target in effect for international transport emissions in the Netherlands; 2) OBPs used for industrial feedstock flows are embedded in products and do not result in GHG emissions until they are incinerated as waste; and 3) refineries produce a significant amount of fuels and OBPs that is exported and does not result in GHG emissions in the Netherlands. Climate policies focused on these factors are necessary for decreasing the amount of fossil fuels used in the 2050 energy system.

The adoption of renewable energies during the transition is reported in Fig. 8, where it can be observed that their use in 2050 is 10 times more than that in 2020. The most pronounced increase is due to the adoption of wind energy (i.e. wind turbines), which accounts for over 40% of all renewables in 2050. Biomass plays a crucial role in the final years when it is being supplied for the production of olefins to produce industrial feedstock in the chemical sector, which, next to biofuels and other biomass sources, account for over 500 PJ, that is, approximately a quarter of the share of renewables. This role of biomass is largely due to the possibility of importing biofuels (330 PJ) and wood (320 PJ) ,[12] the values of which are assumed to be intermediate values provided by the two TNO scenarios for a climate neutral energy system for the Netherlands [54]. The usage of these two energy sources is followed by that of solar energy (i.e. photovoltaics), which comprises approximately 15% of the share of renewables. It is also possible to observe a pronounced role of geothermal and ambient energy used for heating purposes (shown in the graph under other renewables). It is important to mention that the potentials assumed for the adoption of renewable energies are based on sources (Appendix F) that account for the land use of the corresponding technologies (e.g. wind turbines, photovoltaic cells, and space for biomass farming).

To better understand how energy is being used, Table 2 lists the energy flows according to the standard indicators commonly used by CBS in the national energy balance [55]. This table shows a decrease in the final energy usage for the first part of the transition, which is due

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[12] It is well understood that biomass for energy purpose is strongly constrained by the water-food-land nexus, making its future availability a critical uncertainty for the transition. Such nexus was not considered for this study when selecting these potentials. However, the figures are in line with the levels of bio-energy production potentials for 2050 according with the IMAGE model, which estimates 8–15% of the total final consumption [85].

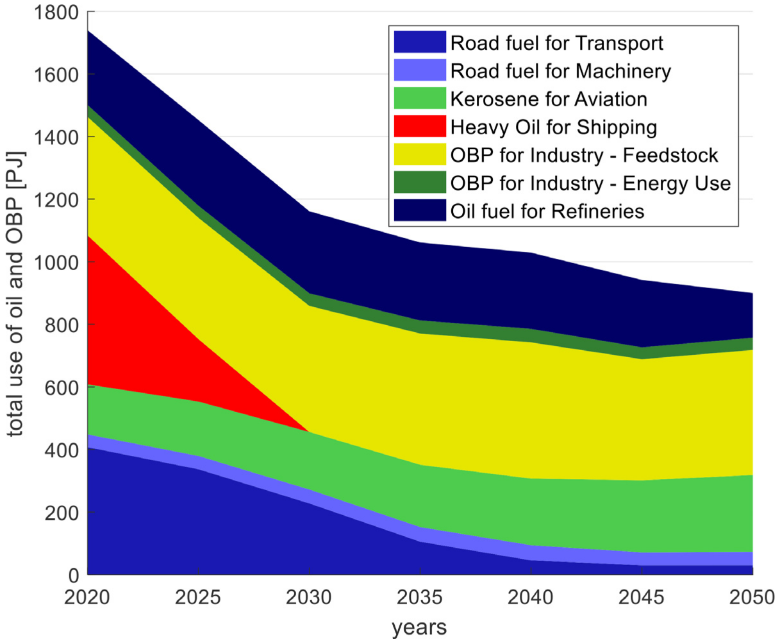

Fig. 7. Long-term evolution of the use of oil and OBPs by activity.[11]

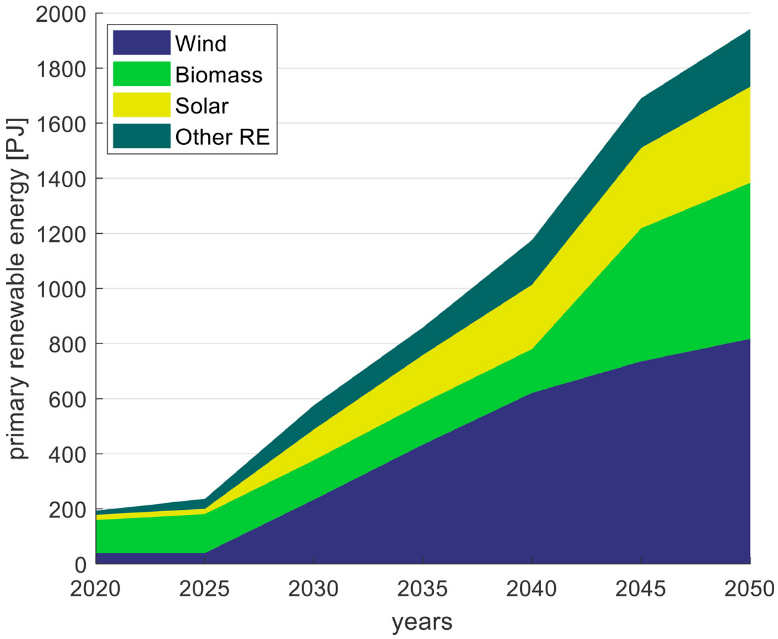

Fig. 8. Long-term evolution of renewable energy production by source.

Table 2
Evolution of the Netherlands' primary and final energy account in IESA-Opt.

Energy Account	Units	2020	2025	2030	2035	2040	2045	2050
Net primary	PJ	3735	3666	3307	3391	3459	3726	3831
Net energy transformations	PJ	680	817	467	529	539	660	656
Total final including international transport	PJ	3168	2959	2955	2981	3037	3178	3291
International transport	PJ	621	666	688	724	758	796	831
Total final excluding international transport	PJ	2547	2293	2266	2257	2280	2382	2460
Feedstock	PJ	482	498	518	534	540	532	538
Final energy use	PJ	2065	1796	1748	1723	1740	1850	1922
Losses in final energy use	PJ	123	105	88	99	74	82	91
Final electricity	PJ	393	404	453	529	629	669	723
Total electricity	PJ	434	443	523	613	783	885	1103

Table 3
Sectoral composition of final energy in 2050.

Sector	Total [%]		Total [PJ]		Heat [PJ]		Electricity [PJ]		Fuels [PJ]		Feedstock [PJ]	
	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050	2020	2050
Residential	16%	13%	395	297	311	205	85	92	0	0	0	0
Services	11%	9%	280	202	150	67	130	135	0	0	0	0
Agriculture	6%	8%	155	185	96	111	37	53	22	21	0	0
Transport	17%	12%	433	276	0	0	8	228	425	48	0	0
Industry	49%	60%	1232	1415	362	297	142	230	245	349	482	539
Total Final	100%	100%	2495	2376	919	681	402	738	692	418	482	539

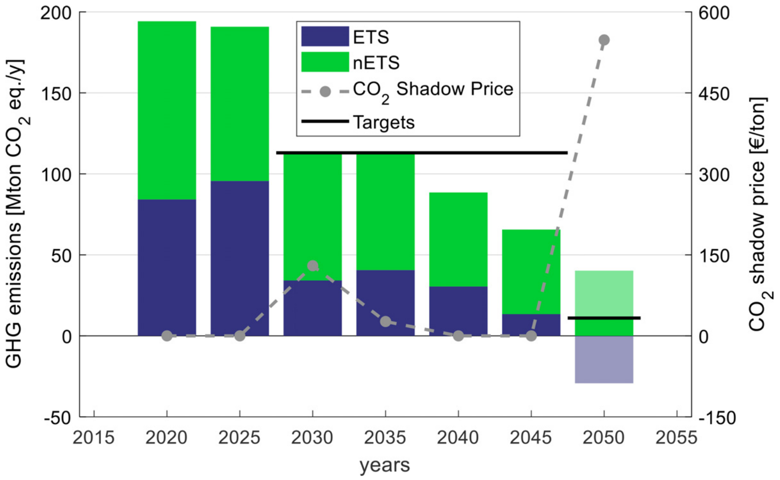

Fig. 9. Long-term evolution of CO$_2$ emission and price in ETS and non-ETS sectors.

to the early retrofitting of all the energy-efficient options (it is important to mention that it is an optimisation model, and thus, the obtained results are not predictions). It is also interesting to note that the sudden decrease in energy transformation in 2030 is mainly driven by the decommissioning of coal generators and an increase in the use of renewable sources in accordance with the 2030 target. Subsequently, the energy transformations increase again as a consequence of the adoption of power generation from gas and owing to the hydrogen production from electrolysis in 2050. Finally, the electrification of activities is evident, as the amount of final electricity used in 2050 almost doubles that in 2020, while the system also uses 9% less final energy.

The sectoral disaggregation of the resulting 2050 final energy consumption is presented in Table 3. Here, we observe that the final energy consumption of all the sectors tends to decrease except in the case of the industrial sector, which, despite efficiency improvements, uses more energy in 2050 owing to an increase in activity volumes. The most evident difference is the significant decrease in transport energy use despite the higher activity volume. This is explained by the electrification of the transport fleet, which reduces conversion losses typically inherent to burning fuels in internal combustion engines. Finally, systemic electrification is completed by the partial electrification of utilities in industry and the adoption of more electric-based machinery in agriculture.

3.2. *Emission pathway*

The climate policy of 45% and 95% emissions reductions for 2030 and 2050, respectively, indicates a maximum of 113 and 11 Mton of CO$_2$ eq. per year, respectively. Based on this, IESA-Opt provides the optimal emission abatement pathway in the ETS and non-ETS sectors for this transition, as shown in Fig. 9. Here, it is shown that the ETS sectors undertake the greatest abatement responsibility as they present a pronounced and accelerated reduction path, while even realising negative emissions in 2050. Interestingly, in the years 2040 and 2045, the system decarbonisation exceeds the 2030 emissions reduction target in a cost-effective manner, as indicated by the null-emission shadow price. Subsequently, when the second reduction target is introduced in 2050, the emission shadow price increased to almost 560 €/ton of CO$_2$. This is almost four times higher than the 2030 shadow price, which indicates that, if the targets are adhered to seriously, the transformation required for the decade after 2040 will impact the system more aggressively than the impact we are experiencing in this decade. However, further research and development efforts can aid in mitigating the extra costs, as the technological learning considered for this scenario is based on conservative projections. In addition, it is worth mentioning that the model does not yet include all of the potentially available decarbonisation options in the industry (as we do not explicitly model furnaces, materials recycling, or highly innovative processes with low readiness indexes), and that new innovative technologies may mature in time to assist the transformation.

The current climate policy focusing on decarbonisation targets only for the years 2030 and 2050 may result in behaviours such as the shadow prices of the emission reduction constraint, as shown in Fig. 9. Hence, in Fig. 10, we compare the current climate policy with two alternative decarbonisation paths in which a) only the 95% emission reduction target in 2050 is considered and b) a linear decrease from 49% reduction in 2030 to 95% reduction in 2050 is followed. This figure shows that even when the target is only imposed in 2050, the system already reduces over 70% of the emissions by 2045. Interestingly, the objective functions of the three presented paths do not differ significantly: for the 2050 target, the value is B€ 314.4; for the 2030 and 2050 targets, the value is B€ 314.8; and for the linear progression, the value is B€ 315.3. However, the system configuration also varies amongst the three cases, especially in the power sector and particularly in the imports and exports of electricity (although the Netherlands becomes a net exporter in these three cases). The most-constrained path (linear progression) presents higher imports and slightly lower exports of electricity for all the years, while the least-constrained path (only a 2050 target) presents the lowest imports and highest exports of electricity. This is owing to the extra room for emissions from thermal generation units, which can provide electricity for national and external demand. Furthermore, the average emissions for the period increased from 111 Mton of CO$_2$/year

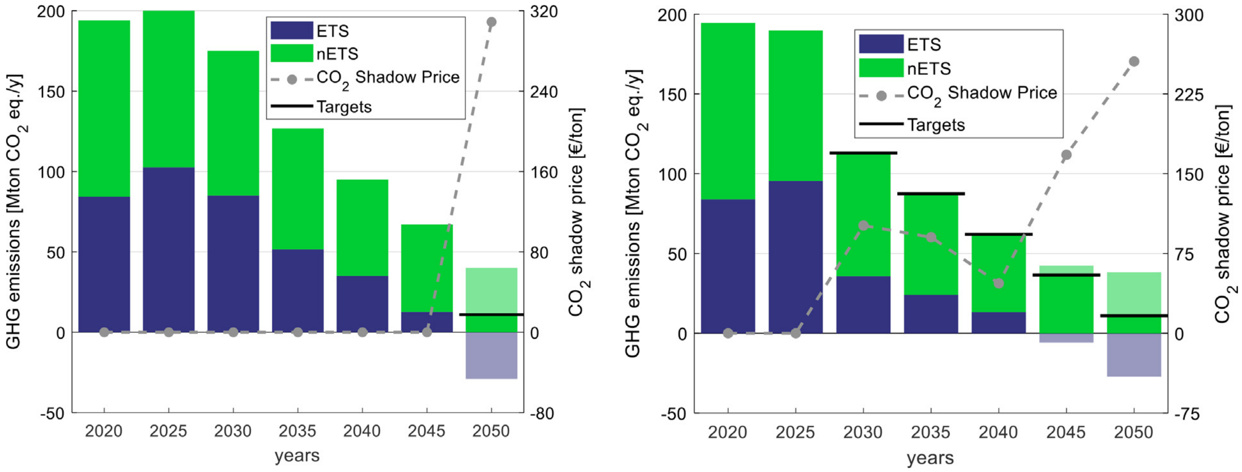

Fig. 10. Alternative climate policy paths for the emission reduction targets. Left: only with a 95% emission reduction target in 2050. Right: linear reduction of the target from 49% in 2030 to 95% in 2050.

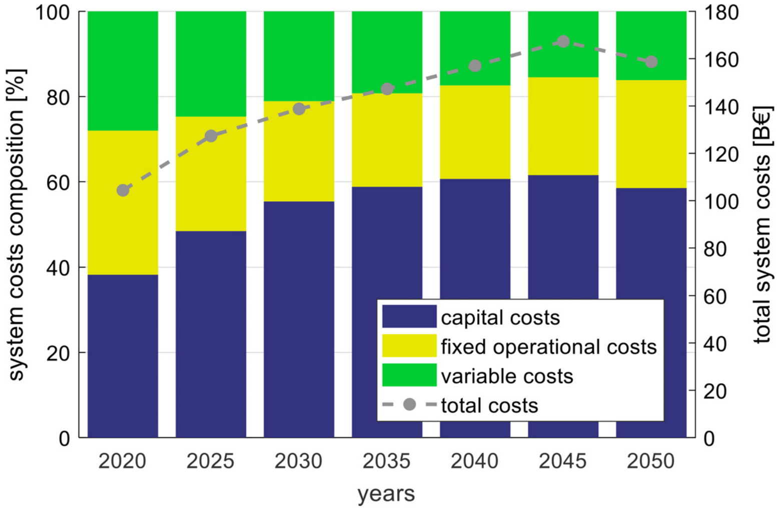

Fig. 11. Long-term system cost evolution.

with the current climate policy of 124 Mton of CO_2/year when the target is only imposed for the year 2050, and decreased to 99 Mton of CO_2/year when the targets are decreased linearly. This observation results in the requirement fora direct recommendation to policy makers to include more intermediate targets for the energy transition, as they could reduce the cumulative emissions by more than 10% while maintaining the transition cost increase at less than 1%.

3.3. System costs

The resulting transition path is characterised by a progressive increase in system costs until 2050, with a slight peak in 2045, as illustrated in Fig. 11. This general upward trend is driven by the climate policy, along with the assumed economic growth and increases in the prices of fossil fuels and biomass. The 2045 peak can be attributed to the effect of the anticipation of the 2050 emission target on the power sector investments and is partially caused by the impact of (exogenous) technological learning. It is important to mention that the anticipation of the target in the power sector results in higher electricity exports in 2045 as both flexible thermal generation and excess intermittent generation can be placed outside the Netherlands easily, as required, while the 2050 target makes this “symbiosis” between thermal and intermittent generators less frequent. Therefore, in 2050, there is a considerable reduction in the electricity export flows as the power system can no longer use CO_2-emitting thermal units freely to provide flexibility to the national (and part of the European) power system. Finally, a switch from variable to capital costs is also observed, which is mainly driven by the adoption of wind and solar energy sources that lack a fuel-cost component. It is important to mention that variable costs, which include both variable operational costs and fuel costs in this graph, decrease both in share and absolute terms, despite the assumed growth in fuel prices (fossil and biomass).

To better understand the cost composition of the system, it is worth analysing the sectoral costs while bearing in mind the cost definitions presented in Table 4. The four cost perspectives included in the IESA-Opt model are as follows: 1) the objective function that considers the problem perspectives on the costs of decisions; 2) the energy prices representing the market perspective of the costs of commodities; 3) system costs, which describe the cost impact of the energy transition at a national scale; and 4) sectoral costs, which address the users’ perspectives on cost for each sector considered in the model. These cost definitions aid in understanding the difference between the system costs presented in Fig. 11 and Fig. 12. In the sectoral costs definition presented in Fig. 12, if a sector uses any form of processed energy (e.g. electricity), it must pay the energy price at the time of use (e.g. producing electricity at a certain hour costs the system less than what the final users pay).[13]

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[13] The electricity price resulting from shadow prices represents the generation cost of the marginal generator, and includes both the capital and operational cost

Table 4
Definitions of the different cost perspectives included in the IESA-Opt model.

Cost Perspective	Definition
Objective function (Problem perspective)	This cost perspective directly reflects the planning and operational decisions in the mathematical problem. Hence, it reflects annualised (and discounted) investments for new and retrofitted technologies, fixed costs of having a technology in the system, capital recovery (if any) of premature decommissioning, and variable operational costs (fuel consumption and other variable costs).
Energy prices (Market perspective)	The energy prices are reflected by the dual variables of the energy balance constraints. Therefore, they reflect the market value of a commodity in the model and are used to account for the energy costs of imports and exports as well as for sectoral costs analyses.
System costs (National perspective)	System costs are obtained after post-processing planning and operational decisions as considered in the objective function. Here, the distinction between the national system and "problem appendices" is made explicit (EU power system, refineries exports, and gas exports). The post-processing accounts for the cross-border trading component of electricity, gas, and OBPs. It should be noted that this form of reporting keeps track of the capital cost component of the planning decisions based on the costs of the decision period and the economic lifetime of the decision.
Sectoral costs (Users' perspective)	Sectoral costs explicitly account for the fuel prices paid by each sector based on the market perspective of the energy costs. This means that the total sum of costs in all sectors will be higher than the system costs, as this definition accounts for the hidden added value of the energy prices. Furthermore, the trading component mentioned for the national system costs is allocated to each specific sector under this definition. Finally, the sectoral cost provides a further disaggregation, as the infrastructure costs are explicitly reported here (while they are regarded as capital and fixed operational costs from the national perspective), which is also the case for the emission ETS costs (which are regarded as variable costs in the system costs definition).

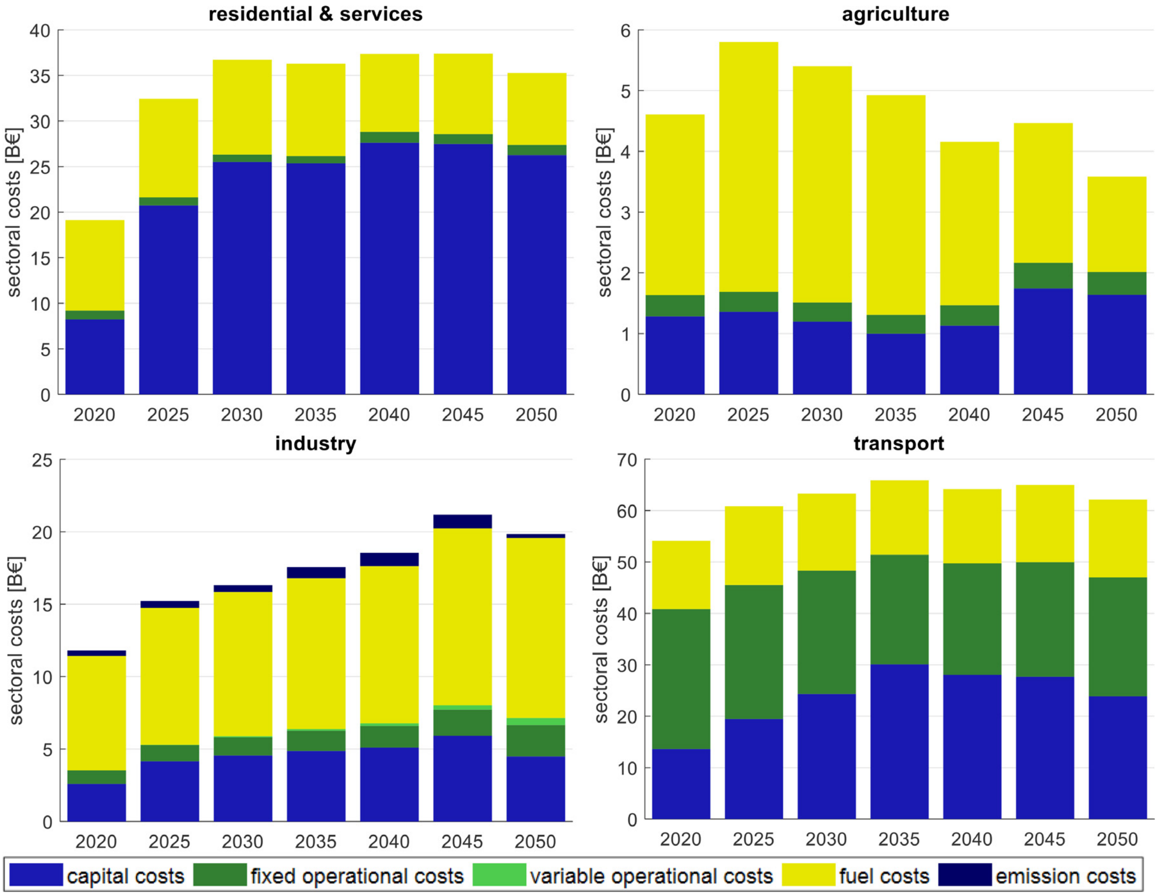

Fig. 12. Sectoral cost disaggregation. Top left: Residential and services sector. Top right: Agriculture sector. Bottom left: Industry sector. Bottom right: Transport sector.

This differentiation of the cost perspectives enables us to observe the different impacts of the transition in all four final sectors from the users' perspective, as shown in Fig. 12. For instance, in the residential and services sectors, there is an immediate adoption of improved space insulation (from the cost optimal perspective), which drives a sudden increase in capital costs and a progressive decrease in fuel costs. In con-

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components of the objective function (as done by other models such as EMMA [86]). However, it is important to mention that when computing shadow prices, it is also possible to fix the installed capacities to get only the operational component represented in the dual variable. The latter would reflect more closely what happens in the Netherlands' energy-only market approach with an imperfect scarcity price, but it does not guarantee that all the generators can recover the investments (this is typically known as the missing money problem). There are different market proposals to address the issue [86], but further elaboration would fall outside of the scope of this study. It is also important to mention that a value of lost load (VOLL) of 3,000 €/MWh (in line with the maximum bid allowed in the EPEX SPOT market) was used to facilitate feasibility, hence it also affect the shadow prices when dispatched.

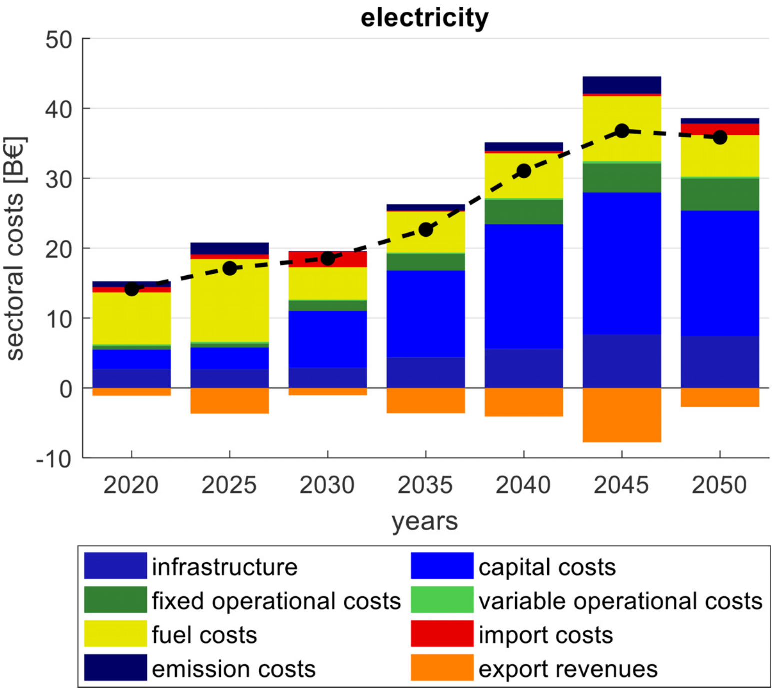

Fig. 13. Cost disaggregation for the electricity sector.

trast, the agriculture sector does not exhibit an increase in the capital cost of energy until late in the transition, while the fuel cost component steadily decreases in the meantime. The transport sector trend shows a progressive increase in the capital intensity until it peaks in 2035, while the fuel cost component remains approximately constant. The latter is a notable result for the sector, as it implies that the decrease in fuel costs brought on by the electric fleet aids in mitigating the increase in fuel costs of the other transport activities. Finally, the industrial sector is affected by an increase in capital, fuel, and emission costs, and it also shows a decrease in costs from 2045 to 2050, which is apparent in the total system cost figure. This occurs because many industrial activities wait until cheaper technology is available in 2050, which results from the steep technological learning in the sector (exogenous).

The electricity sector costs, as shown in Fig. 13, are also interesting to explore, as this sector hides many elements that influence the evolution of the total system costs. In addition to the substantial increase in power sector costs, this graph evidences the close relationship between electricity trading and the emission reduction target from the optimality perspective. When climate policy is adopted in 2030 and 2050, it directly affects the freedom of the system to use fossil-based generation, which is reflected in an increase in import costs and a significant decrease in revenues from exports. Furthermore, the assumed climate policy results in a complete decommissioning of coal power plants in 2030, which are substituted by over 30 GW of VRES capacity, which drives the reduction of fuel costs. Subsequently, the VRES adoption continues as the installed capacity is increased to over 170 GW, which is supplemented by a steady increase in cross-sectoral flexibility, storage (compressed-air energy storage (CAES)), and the use of available thermal capacity (namely, combined cycle gas turbines), which results in a significant increase in exports. Finally, the accentuated electrification and the increasing shares of VRES drive a progressive expansion of the electricity network, which contributes to the reported increase in system costs.

3.4. System configuration

All the outcomes of a scenario run are related to the technological configuration of the system. IESA-Opt can simultaneously determine the cost-optimal technological stock (and its usage) of various sectors for the considered transition period. Table 5 presents an overview of the use of all the technologies required for satisfying the main sectoral activities for the entire transition. This reported trend shows that the model choices switch toward greener alternatives.

For instance, the industrial sector starts adopting novel technologies such as electrolytic steel production [56] or solid state ammonia synthesis (SSAS) for ammonia production to reduce emissions by electrification. In addition, electrolysers are being adopted at both decentralised and centralised locations to produce hydrogen mainly for refineries. In addition to electrification, other decarbonisation paths can be observed in the industry sector, such as the use of biomass to produce olefins and the adoption of heat from biomass with CCUS to provide negative emissions. As a general observation, CCUS is widely adopted in the industrial sector owing to its high CO_2 storage capacity and the possibility of using it as a sink (e.g. the production of synthetic fuels from electricity and CO_2 in 2050).

The transport sector also undergoes a complete transformation. The model run of the reference scenario results in the predominant presence of electric vehicles (EVs) as the cost-optimal configuration for the road subsector. Similarly, within the navigation subsector, heavy oil ships were substituted with compressed-natural-gas-engine (CNG-engine) ships. The rest of the transport sector remains largely unchanged, primarily because trains are already electric and because emissions from kerosene planes are not addressed by the existing climate policy.

For the residential and services sectors, the model determines the optimal path for retrofitting all the spaces to the maximum level of insulation as quickly as possible. It then uses boilers, district heating, and electric heat pumps to meet the reduced residential heat needs and gas CHPs and hybrid heat pumps to supply heat for service spaces. A system running on geothermal energy and hot water storage tanks is adopted by the scarcely used district heating network to provide flexibility to the supply.

Similarly, the agriculture sector uses geothermal energy to satisfy its heat demand. However, this outcome would be different if spatially sensitive data were used to only allow certain regions to adopt geothermal energy according to its availability.

It is also important to highlight the role that retrofitting plays in determining the cost-optimal system configuration, as it provides a signif-

Table 5
Evolution of the system configuration for different sectors. .[14]

Sector	Activity	Technology	Units	2020	2030	2040	2050
Industry	Steel production	Blast furnace	Mton	6.9	6.7	4.5	0.0
		Blast furnace with CCUS	Mton	0.0	0.0	0.0	4.5
		Hisarna	Mton	0.1	0.0	0.0	0.0
		Hisarna with CCUS	Mton	0.0	0.0	0.5	0.0
		ULCOWIN	Mton	0.0	0.0	1.9	2.8
	Ammonia production	Haber Bosch	Mton	2.8	0.8	0.0	0.0
		Haber Bosch improved	Mton	0.0	0.9	0.0	0.0
		Haber Bosch improved with CCUS	Mton	0.0	1.2	2.1	1.7
		Solid State Ammonia Synthesis (SSAS)	Mton	0.0	0.0	1.0	1.7
	Petrochemical transformation	Naphtha steam cracker	Mton	7.2	0.4	1.1	0.0
		Naphtha steam cracker improved	Mton	0.0	7.2	7.2	0.0
		Naphtha steam cracker improved with CCUS	Mton	0.0	0.0	0.0	7.4
		Olefins from biomass	Mton	0.0	0.1	0.0	1.3
	Industrial heat	Boiler gas	PJ	237.1	83.6	83.5	0.0
		Boiler coal	PJ	3.0	0.0	0.0	0.0
		Boiler coal with CCUS	PJ	0.0	0.0	17.3	0.0
		Boiler biomass	PJ	0.0	42.7	0.0	0.0
		Boiler biomass with CCUS	PJ	0.0	30.8	30.0	94.3
		CHP gas	PJ	58.0	0.2	0.3	0.0
		CHP biomass	PJ	0.8	9.9	0.3	0.1
		CHP biomass with CCUS	PJ	0.0	0.3	40.4	100.4
		Electric heat pump	PJ	0.0	50.6	50.6	50.6
		Geothermal heat pump	PJ	0.0	43.9	46.8	65.5
Transport	Motorcycles	Internal combustion engine (ICE) vehicle	Gvkm	4.8	5.7	4.1	0.3
		Electric vehicle	Gvkm	0.3	0.2	2.4	6.9
	Cars	ICE vehicle	Gvkm	108.3	64.6	0.0	0.0
		PI Hybrid vehicle	Gvkm	1.1	0.3	0.0	0.0
		Electric vehicle	Gvkm	1.1	49.5	119.2	125.3
	LDV	ICE vehicle	Gvkm	20.9	13.8	0.0	0.0
		Electric vehicle	Gvkm	0.1	10.4	27.4	32.3
	HDV	ICE vehicle	Gvkm	7.4	6.5	0.6	0.0
		Electric vehicle	Gvkm	0.0	1.1	7.4	8.3
	Buses	ICE vehicle	Mvkm	298.2	28.1	0.0	0.0
		Natural gas vehicle	Mvkm	305.0	584.0	332.3	0.0
		PI Hybrid vehicle	Mvkm	2.4	1.2	0.0	0.0
		Electric vehicle	Mvkm	11.6	11.1	305.0	650.0
	International navigation	Heavy oil ship	Mvkm	110.0	0.0	0.0	0.0
		CNG ship	Mvkm	0.0	125.0	135.0	145.0
Residential	House insulation	Insulation level GFE	Mhouses	2.1	0.0	0.0	0.4
		Insulation level DC	Mhouses	3.0	0.0	0.0	0.1
		Insulation level B	Mhouses	1.9	0.0	0.0	0.0
		Insulation level A	Mhouses	0.9	0.3	0.2	0.0
		Insulation level *A*+	Mhouses	0.4	8.5	9.1	9.2
	Heating technology	Boiler gas	PJ	249.2	187.5	176.4	169.2
		Boiler gas with wood stove	PJ	49.0	1.4	0.0	0.0
		Boiler gas with solar heater	PJ	1.0	1.0	0.0	0.0
		District heating	PJ	0.0	0.3	3.5	15.0
		Hybrid heat pump	PJ	10.0	6.2	0.0	0.0
		Electric heat pump	PJ	1.5	5.7	20.8	20.8
Services	Space insulation	Insulation level GFE	Mm^2	190.0	0.0	0.0	0.0
		Insulation level DC	Mm^2	100.0	0.0	0.0	0.0
		Insulation level B	Mm^2	210.0	0.0	0.0	0.0
		Insulation level A	Mm^2	10.0	0.0	0.0	0.0
		Insulation level *A*+	Mm^2	5.0	540.0	555.0	560.0
	Heating technology	Boiler gas	PJ	127.8	27.8	0.0	0.0
		District heating	PJ	3.7	0.0	0.0	0.0
		Hybrid heat pump	PJ	10.0	5.0	26.0	26.0
		Electric heat pump	PJ	3.0	1.5	0.0	0.0
		CHP gas	PJ	6.0	36.9	43.5	40.5
Agriculture	Machinery	Fuel based	PJ	20.7	23.8	27.7	12.0
		Hybrid	PJ	2.1	1.5	0.0	18.2
	Heating technology	CHP gas	PJ	81.3	69.3	24.6	0.1
		Geothermal heat pump	PJ	5.6	22.4	72.2	100.0
		Shallow soil energy heat pump	PJ	0.3	0.3	0.0	1.5
		Boiler gas	PJ	8.2	8.8	9.2	9.6

(*continued on next page*)

Table 5 (*continued*)

Sector	Activity	Technology	Units	2020	2030	2040	2050
Refineries	Oil refining	Deep cracking	PJ	554.0	1234.2	949.3	0.0
		Deep cracking with CCUS	PJ	0.0	0.0	210.2	1068.8
		Basic cracking	PJ	649.0	0.1	0.0	0.0
		Basic cracking with CCUS	PJ	0.0	150.2	0.0	0.0
		Koch refinery	PJ	18.0	0.0	0.0	0.0
		Koch refinery with CCUS	PJ	0.0	19.0	22.8	26.6
		Power to liquids	PJ	0.0	0.1	1.3	84.4
		Biorefineries	PJ	23.0	15.0	0.1	0.0
		Biorefineries with CCUS	PJ	0.0	0.0	25.0	25.0
Heat Network	Heating technology	Boiler Gas	PJ	3.5	0.0	0.0	0.0
		Geothermal gas heat pump	PJ	0.0	0.1	3.0	14.7
		Hot water storage tank	PJ	0.2	0.3	1.9	7.0
Hydrogen	Hydrogen production	Alkaline electrolyser	PJ	0.0	0.0	0.8	78.0

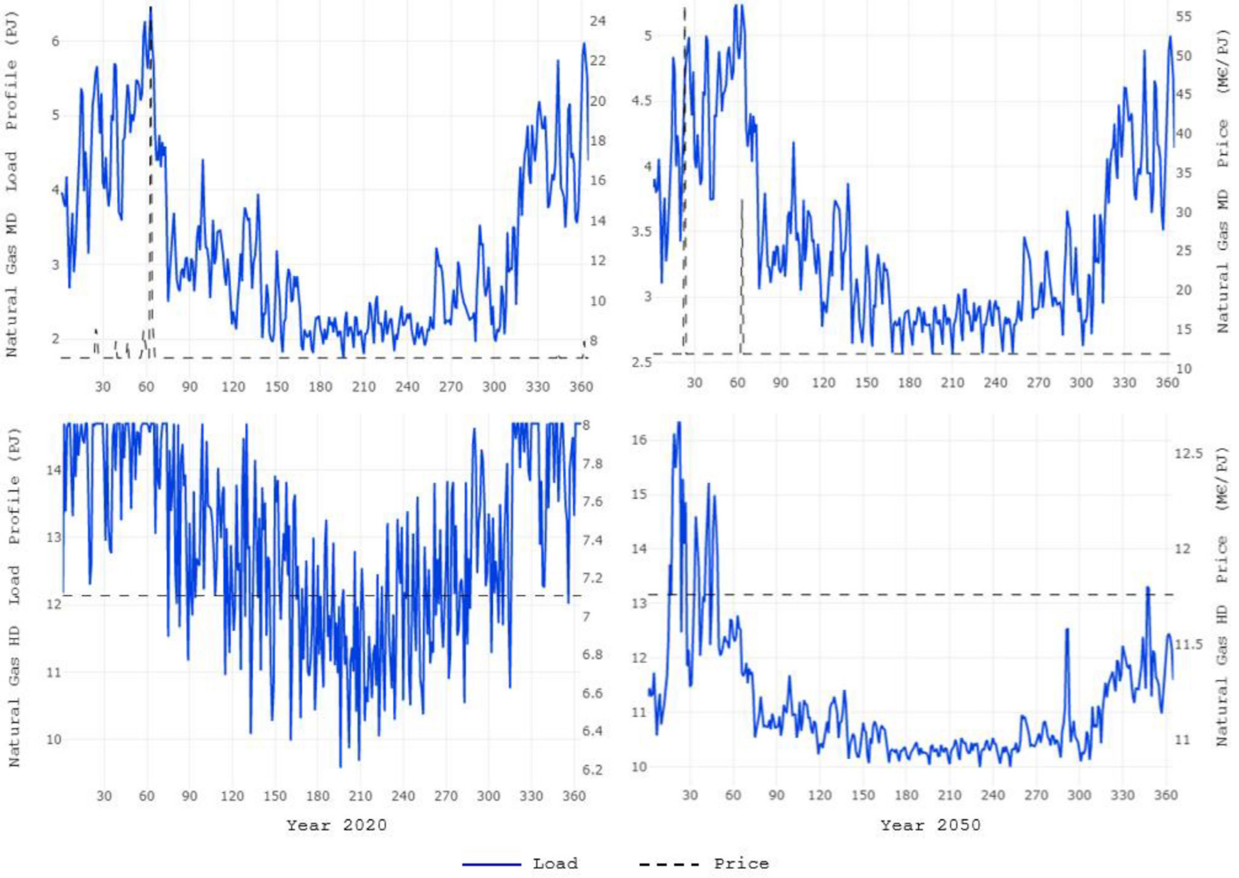

Fig. 14. Daily loads and respective prices of natural gas networks in 2020 and 2050.

icant amount of flexibility for investments. The obtained system configuration perfectly illustrates the advantage of this modelling capability, especially in terms of efficiency improvements and the adoption of CCUS modules, which are adopted by the system progressively as the system needs them to meet the decarbonisation targets.

3.5. Temporal dynamics of gas networks

In contrast to the electricity network, the IESA-Opt balances the gaseous networks in daily time frames [17]. This modelling choice provides the advantage of observing seasonal variations while maintaining low computational requirements. For instance, the seasonal variation in the natural gas network is presented in Fig. 14. The medium density (MD) network appears similar in 2020 and 2050 because MD network is connected to the built environment heating, and we use the same reference profile for built environment technologies. However, compared to 2020, their operation is less dispersed in 2050 (i.e. lower maximum and higher minimum), which is due to the larger network buffer capacity along with the increased role of sectoral integration and increased use of long-term hot-water storage in BE. Compared to 2020, the variation in the high-density (HD) network noticeably reduces, primarily because of a decrease in the use of gas-fired electricity generators. However, the HD network remains the main national medium for heating purposes in 2050; therefore, its behaviour resembles that of the MD network. Moreover, the large minimum operating value of the HD network relates to high levels of imports and exports (assumed to have a flat profile in this study), which indicates the key role of the Netherlands as a European natural-gas hub.

IESA-Opt represents the CCUS and hydrogen networks with daily balances, and its operation in 2050 is shown in Fig. 15. Both hydro-

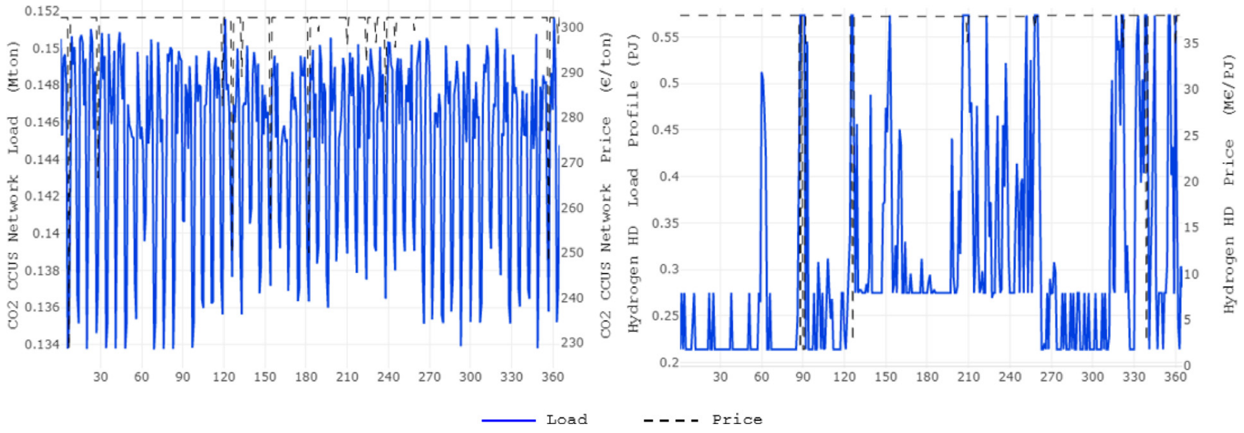

Fig. 15. Daily loads and respective prices of CCUS and hydrogen networks in 2050.

Table 6
Evolution of power sector configuration.

Sector	Activity	Technology	Units	2020	2030	2040	2050
Power	High voltage	Offshore wind	PJ	14.0	176.3	554.7	736.2
		Coal old	PJ	53.2	0.0	0.0	0.0
		Co-fired coal	PJ	73.5	0.2	0.0	0.0
		Co-fired coal with CCUS	PJ	0.0	0.0	0.0	0.0
		CCGT	PJ	116.4	19.9	123.0	47.7
		CCGT with CCUS	PJ	0.0	0.1	0.3	0.1
		CCGT from BFG	PJ	5.2	0.0	0.0	0.3
		GT	PJ	0.1	0.0	0.0	0.8
		Nuclear	PJ	14.4	14.5	0.0	0.0
		Biomass	PJ	0.1	0.1	0.1	0.1
		Compressed-air above-ground storage	PJ	0.0	8.6	11.8	14.9
		Compressed-air underground storage	PJ	0.0	11.4	93.1	144.0
		Import from BE	PJ	8.8	5.9	12.2	38.2
		Import from DE	PJ	44.4	75.0	13.9	35.4
		Import from DK	PJ	7.8	7.2	8.8	11.4
		Import from NO	PJ	9.0	9.1	13.1	15.6
		Import from GB	PJ	1.0	5.5	9.4	15.3
		Transformers to HV	PJ	1.7	9.3	30.5	30.5
	Medium voltage	Hydro power	PJ	0.4	0.4	0.3	0.3
		Onshore wind	PJ	25.5	57.4	67.0	81.0
		Solar PV fields	PJ	3.1	13.8	37.8	67.2
		Industrial solar PV	PJ	5.9	42.0	84.0	112.0
		Transformers to MV	PJ	123.0	19.2	43.6	134.7
	Low voltage	Residential solar PV	PJ	9.8	56.0	112.0	168.0
		Transformers to LV	PJ	112.1	217.4	286.2	284.7

gen and CO_2 exhibit a seasonal behaviour owing to the availability of cheaper electricity in the summer. Lower electricity prices promote the use of electrolysers in the summer, which consequently triggers an increased use of CO_2 from the CCUS network to produce synthetic fuels. The high variability in the hydrogen network is due to its limited adoption (i.e. P2L). If hydrogen were to be adopted for more uses, the hydrogen buffer would become a more important measure for mitigating network expansion costs, thus resulting in a more homogeneous profile. Finally, the CCUS network exhibits a strong weekly pattern, which can be explained by its connectivity to industrial technologies, which were assumed to follow “low-weekend” operational profiles owing to the lack of available data for the industry sector.

3.6. Power sector

One of the advantages of the approach adopted in IESA-Opt is that it considers both the long-term and short-term dynamics of the power sector, the intra-year operation of which comprises a complex process that mixes demand-side and supply-side variabilities (e.g. VRES). The long-term supply is reported in Table 6, which shows the technologies used to generate electricity for the various network levels considered in the system.[15] This table shows that the entire system is being supplied energy almost entirely by VRES by 2050, while it still uses combined-cycle gas turbines for peak hours and complements the flexible supply with considerable amounts of CAES.[16] Another observation is that the required installed capacity of transformers increases as the generation becomes increasingly variable and decentralised. This means that although the conversion losses increase, the system requires considerable network flexibility to optimally balance supply and demand amongst all the options located at various voltage levels along the network (such as imports and exports, electrified industrial activities, and EVs).

Another key capability of IESA-Opt is its ability to provide shadow prices for energy carriers, which is especially useful for electricity networks. These prices are obtained by solving the dual variables of the

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[15] Only the annual generation values and technologies of the sector are reported in the table, which means that the generation of CHPs cannot be found in this table. The evolution of the installed capacities and the complete list of demand and supply technologies may be referred to on the web portal of the model [22].

[16] Storage technologies are not generators, but in this case, we are reporting the electricity from discharging.

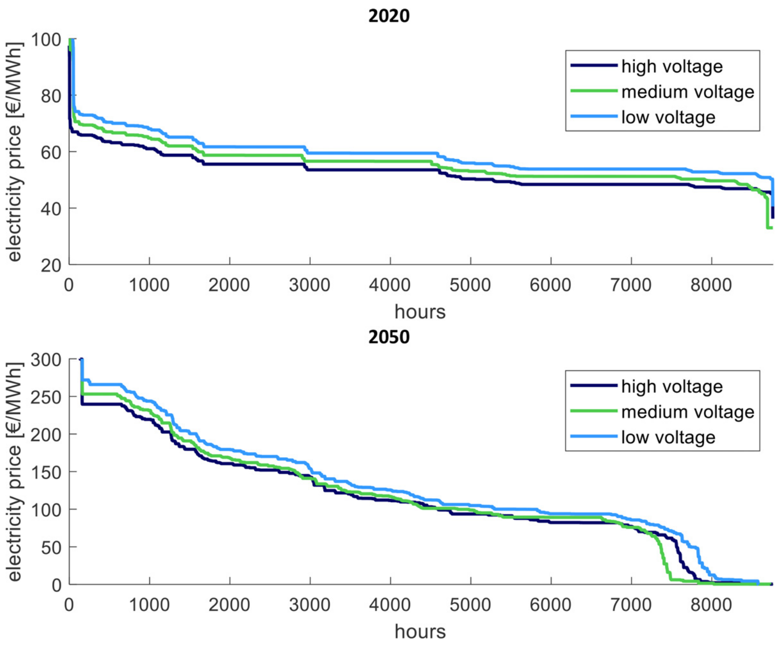

Fig. 16. Duration curve of shadow prices for the different electricity networks considered in the Netherlands' power system representation. Top: Year 2020. Bottom: Year 2050.

hourly balance constraints for the electricity grid, and they only represent the energy component of the despatch, as there are no reserves depicted in the model. As an illustration of this capability, Fig. 16 presents the 2020 and 2050 price duration curves for this scenario for the three electricity networks modelled in the Netherlands. There are two main observations to note here: the increase in prices and the wider spread of price events. The higher presence of VRES in the system triggers a significant number of hours with low electricity prices owing to the corresponding low marginal cost of operation. However, VRES cannot only satisfy the system demand of electricity, but also requires other elements of the system to operate: dispatchable units in the Netherlands and Europe, cross-border electricity flows, batteries and storage technologies, and cross-sectoral flexibility alternatives. It should also be noted that natural gas and CO_2 ETS prices are assumed to increase significantly by 2050 in the scenarios, which, in combination with the aforementioned flexible operation technologies, drive the increase in prices. It is interesting to note that the medium-voltage grid appears to present the highest number of events with low electricity prices in 2050. This indicates the highest potential for photovoltaics in this scenario, which was supposed to be available for connection in the medium-voltage grid. This is a clear example of how congestion points at different voltage levels of the grid (and, although not considered here, is even more important at different locations) can strongly influence the grid requirements for flexibility.

The resulting system configuration presents a considerable increase in electricity flows, with almost triple the 2020 net system load by 2050. This effect is simultaneously driven by an increase in the external trading flows as well as by a profound electrification of both the final and energy sectors, as shown in Table 7. It can be observed that the Netherlands evolved from a net importer to a net exporter, with an increase in volume facilitated by the resulting interconnection capacity expansions.[17] Similarly, by 2050, the system more than doubles its electrification, which is triggered by the adoption of industrial technologies such as ULCOWIN and SSAS, (moderate) electrolyser use, deployment of the electric transport fleet, and choice of electric technologies for heating. Finally, it is worth highlighting that the maximum level of system curtailment is less than 50 PJ, which accounts for less than 5% of the electricity produced by VRES in 2050. Such efficient use of VRES electricity is fundamentally enabled because of the crucial role of cross-sectoral flexibility.

Table 7
Evolution of important electricity parameters.

Electricity volumes	Units	2020	2030	2040	2050
System load	PJ	439.5	497.7	1065.3	1287.1
Imports	PJ	73.2	105.6	59.0	119.5
Exports	PJ	78.2	78.2	337.7	305.0
Net	PJ	434.5	525.1	786.5	1101.7
Final use	PJ	402.0	464.5	638.9	738.1
Curtailment	PJ	0.1	1.3	22.6	43.3
Average price	€/MWh	40.0	41.9	29.5	28.1
Price variability	€/MW	0.6	8.0	5.3	6.9
Total electrification	%	11.6	15.9	22.7	28.8
Final electrification	%	20.0	27.5	38.3	40.2

3.7. Cross-sectoral flexibility

The ability to describe the sectoral potentials to provide system flexibility in allocating electricity from VRES is one of the key capabilities of IESA-Opt. Fig. 17 presents the cost-optimal evolution of cross-sectoral flexibility volumes required to integrate a large share of VRES according to the archetypes considered in the model (Section 0). The most apparent result is the steep increase in the cross-sectoral flexibility in the system from a landscape in which only CHPs deviate from their hourly operation profiles to cope with the power system dynamics to a landscape in which almost all the archetypes are actively deviating. Only the flexibility of CHPs (provided by 13 technologies located in the waste, heat for services, heat for LT and HT, and agriculture subsectors) decreases by 2050, which is in line with the decrease in the use of CHPs. Furthermore, the shedding archetype exhibits the most pronounced role as a cross-sectoral flexibility provider and is mainly driven by the adoption of electrolysers for the hydrogen network, ULCOWIN for steel production, SASS for ammonia production, and in situ refineries' electrolysers for production of road fuels for export (as reported in Table 5). Similarly, storage also provides a significant amount of flexibility and is led by under- and above-ground CAES (as reported in Table 6). Finally, the transport sector also has a share in the contribution; however, it is primarily in the form of smart charging rather than vehicle-to-grid.

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[17] This scenario allows the model to double the existing interconnection capacities of the Netherlands after 2040.

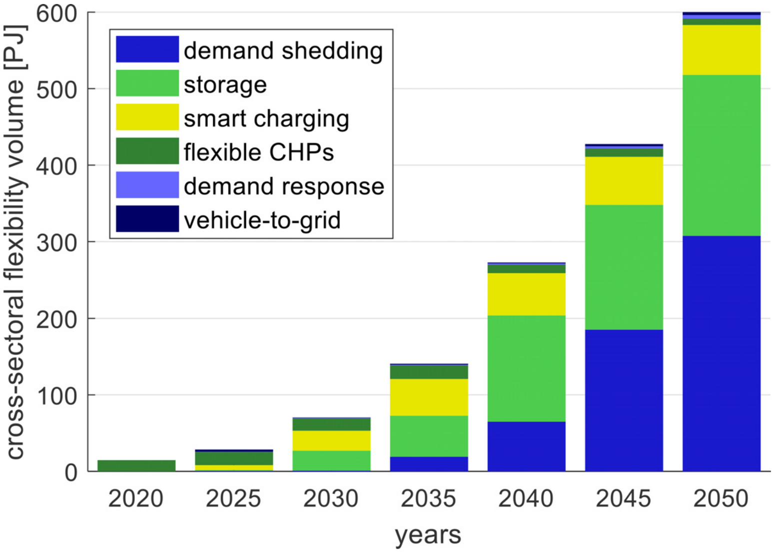

Fig. 17. Evolution of the cross-sectoral flexibility volumes in IESA-Opt. This indicator measures the total amount of electricity demand that was displaced from the original operational profile. The storage volume reported in this graph corresponds to the charging electricity volume.

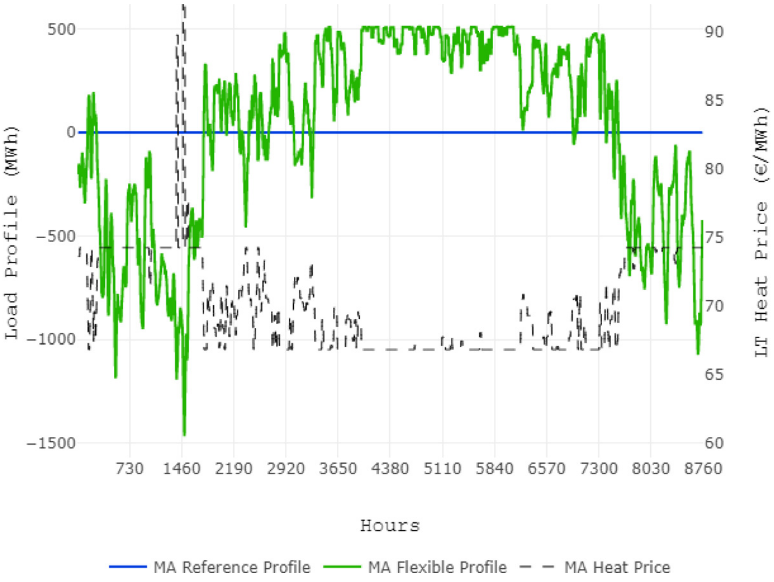

Fig. 18. Daily moving average of hot-water buffer load profile and the respective heat prices in the LT heat network.

Cross-sectoral flexibility is a key capability of IESA-Opt, but it requires a significant amount of data gathering and technology description effort to be able to provide even more insightful analyses. The current flexibility descriptions in the model are focused on few technologies; therefore, it is recommended that the list of technologies that can provide flexibility be expanded. This expansion is expected to influence the lowering of transition costs and reshaping of cost-optimal system configuration.

Using the hourly time-steps approach instead of the time-slice method, we can observe the seasonal behaviour of technologies, such as long-term heat storage. Fig. 18 presents the load profile of the hot-water storage buffer that is connected to the low-temperature heat network. The seasonal trend indicates that the heat storage is charging when the heat demand is low during the summer months and discharging when the heat demand (and price) is high during winter months. The charging and discharging behaviours are directly related to the heat price (i.e. shadow price) of the LT network. Therefore, the storage discharges optimally when prices increase (assuming intra-year perfect foresight).

Other technologies such as ULCOWIN, SSAS, electrolysers, CHPs, and underground CAES demonstrate interesting seasonal behaviours that can be referred to online through the model's portal.

The use of the hourly temporal resolution enables the model to analyse short-term flexibility options, such as the demand response. Fig. 19 presents the load profile of the demand response on a random day. Here, the maximum shifting time frame is one day; hence, the sum of the area between the reference profile (i.e. blue line) and flexible profile (i.e. green line) is zero at the end of each day. Moreover, the flexible profile exhibits an increase in consumption at mid-day hours when the nodal electricity prices (i.e. shadow prices) are lower.

4. Sensitivity analysis

The results presented above correspond to the single run of the scenario presented in Section 0. However, the energy transition is strongly dependant on the denouement of uncertainties, and a practical method of addressing such uncertainties in optimisation models is via sensitivity analyses. To exemplify the usefulness of the model in this arena and explore the relevance of key elements observed in the results, we present four sensitivity exercises in this section: 1) the exploration of different climate policy targets for GHG emissions reduction under four scenarios with different levels of biomass and CO_2 storage availabilities; 2) an analysis of the impact of the different demand streams of oil and

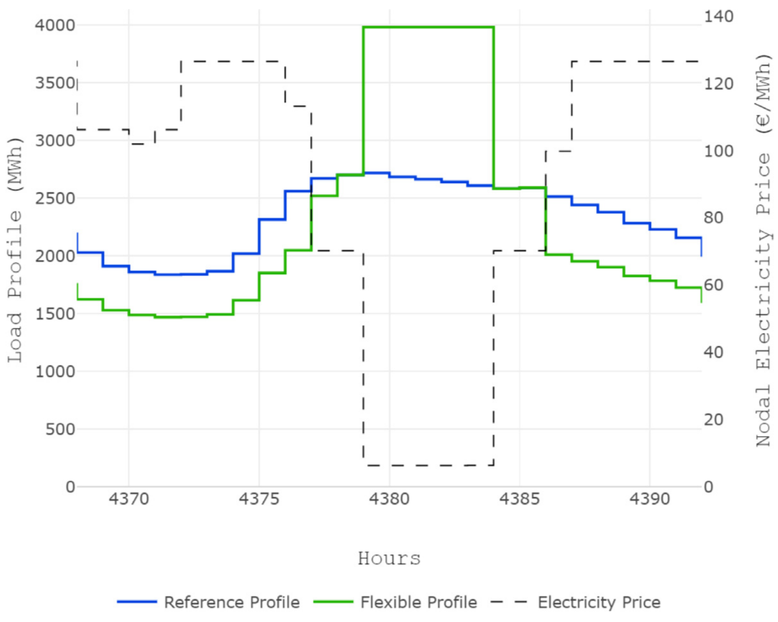

Fig. 19. Reference and flexible profiles of demand response in residential sector in 2050.

Table 8
Description of the scenarios used for the sensitivity analysis presented in section 0.

Scenario	Description	2050 potentials			
		CO_2 storage [Mton CO_2]	National wood [PJ]	Imported wood [PJ]	Imported biofuels [PJ]
HCHB	High availability of biomass and CO_2 storage	50	120	320	330
LCHB	High availability of biomass and low availability of CO_2 storage	25	120	320	330
HCLB	Low availability of biomass and high availability of CO_2 storage	50	60	0	0
LCLB	Low availability of biomass and CO_2 storage	25	60	0	0

OBPs; 3) a bi-dimensional exploration of the role of imported biomass availability and its corresponding cost; and 4) the sensitivity around the demand drivers of key sectoral activities. Finally, it is important to mention that over 100 runs were required to build a different sensitivity analysis. Therefore, we optimised the energy system for the year 2050 only, and we could thus decrease the computational time from 8 h to 30 min per run.

4.1. Change in CO_2-reduction target from 80% to 130%

One of the most interesting features of the transition from the integrated-energy system perspective corresponds to the possibility of achieving negative emissions. To explore this topic, the following exercise presents an analysis focused on three aspects: the climate policy reduction target, the availability of biomass, and the availability of CO_2 storage capacity. This analysis is based on two modifications of the scenario described in Section 0, with different levels of CO_2 storage and biomass availability; the resulting four combinations are presented in Table 8, wherein the HCHB scenario uses the same values as the reference scenario used for the results in Section 0.

These four scenarios were tested with different emissions reduction targets (i.e. ranging from no target to a 130% emissions reduction) in order to analyse the interaction between biomass and CO_2 storage with respect to the level of system decarbonisation. As a result of this exercise, Fig. 20 demonstrates the objective function,[18] shadow price of the emission constraint, average abatement cost[19] (AAC), and curtailment of intermittent renewable electricity generation.

The obtained results are relevant as they present the increase in system costs against different decarbonisation levels. For instance, the social costs increase between 2% and 8% owing to the current climate policy of 95% GHG emissions reduction and variation in the biomass and CO_2 storage availabilities. This highlights two findings: the significant impact of the biomass and CO_2 storage potentials in aiding the decarbonisation of the system affordably, and the significance of ensuring that biomass and CO_2 storage are generously available in the future, as this could not only aid in reducing transitional costs but also to aim for a more ambitious climate policy. This can be observed not only in the values of the different objective functions, but also in the fact that both the shadow price of CO_2 and the ACC for the LCLB scenario at the 95%-reduction target are almost identical as in contrast to the HCHB scenario with a 115%-reduction target.

Finally, an interesting result is that the curtailment in 2050 varies in the same range of 20–130 PJ per year for all four scenarios, where the lower availability of biomass and CO_2 storage results in a lower curtailment for each GHG-reduction target. The explanation for this is that the maximum deployment levels for VRES are reached for the four scenarios even when no target is being enforced. Therefore, a more stringent

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[18] The objective-function value corresponds to the total system costs, which include the costs of the national energy system of the Netherlands plus the European power system costs and the costs of exported refined OBPs for the Netherlands.

[19] The average cost paid to stop emitting a ton of CO_2, obtained as the total system cost increase with respect to the uncapped scenario divided by the tones of CO_2 emissions avoided in each target scenario.

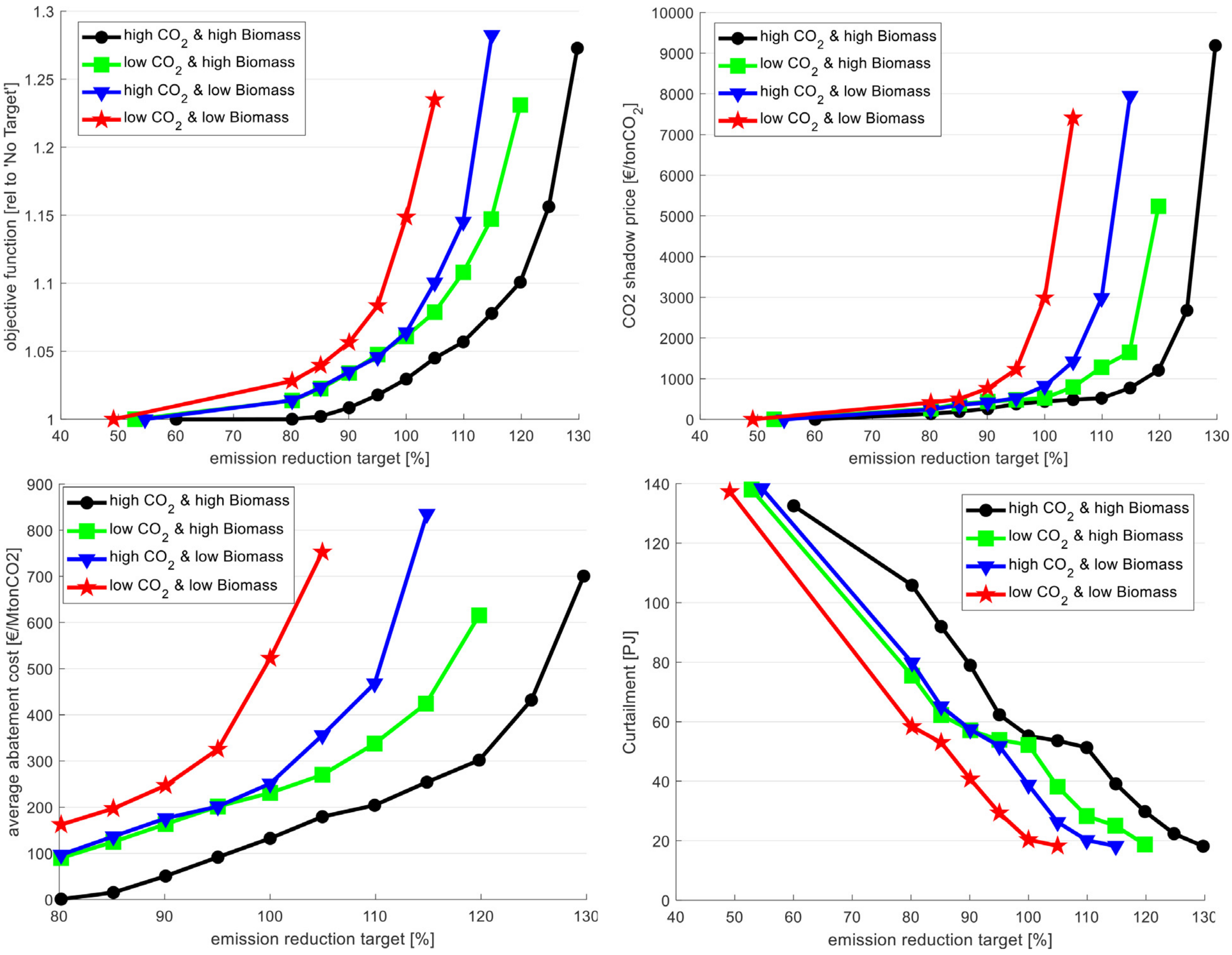

Fig. 20. Results of the sensitivity analysis modifying emissions reduction targets and CO_2 storage and biomass availability in 2050.

target results in a more extensive use of what would otherwise be curtailed electricity, as it makes expensive electrifying technologies more competitive.

For all these observations, both the LCHB and HCLB scenarios stay in the middle of the LCLB and HCHB results, suggesting that both potentials are equally important for decarbonising the system. However, it is also evident that, for scenarios with negative emissions, the availability of biomass is more beneficial for the system.

Analysis of the dynamics of electricity imports and exports is performed to expand the previous sensitivity study. Fig. 21 presents a comparison of the import and export electricity flows for 2050 with respect to the increase in the emissions-reduction target for the four aforementioned scenarios. It is important to mention that, for all these runs, the installed capacities of the European nodes remained unchanged, as reported in Appendix G.

The first observation is that the cases with the minimum and maximum targets present the same flows for all four scenarios, which hints at some possible maximum and minimum trading operation levels for the system. The second observation is the progressive increase in imports and a decrease in exports as the emissions-reduction target is increased. This happens because a looser target allows for cheaper electricity options that can compete in the European market over more hours, while at the same time, imported electricity is considered by the model as clean electricity since it does not increase the national emissions account.

A conclusion from this exercise is that a higher availability of CO_2 storage and biomass provides the system with an enhanced ability to export electricity. It can be observed that, for the same targets, the HCHB scenario exports more electricity than the LCHB and HCLB scenarios, which share similar trends, and the export flows are lower for the LCLB scenario.

4.2. Sensitivity with respect to oil demand streams

Even in a highly decarbonised scenario, as presented in Section 0, oil still plays a significant role in the energy mix. According to Fig. 7, there are three main demand streams remaining in 2050 for oil or OBPs: kerosene for aviation, oil for refineries, and OBPs as feedstock for the petrochemical industry. These manage to bypass the emissions-reduction target as they hardly account for any emissions considered within the target. For instance, emissions from international transport are considered as national emissions only in international waters or for landing and take-off, which comprise less than a quarter of the total emissions. Furthermore, the refineries in the Netherlands export the majority of their produce, and the emissions resulting from the oil fuelling process are captured. Similarly, OBPs used for petrochemical feedstock are mostly embodied in the produce, and fuel-related emissions are treated with CCUS. Therefore, a parallel set of climate policies is required to address these topics. For this exercise, we analyse two different policies and a scenario description to measure their effects in the system: 1) a 95% emissions-reduction target for international transport, 2) a technology ban on oil-based processes for the petrochemical sector, and 3) the elimination of oil-based road-fuel exports by 2050. The scenarios adopted for this analysis are presented in Table 9, Scenario descriptions for the sensitivity analysis of oil demand streams.

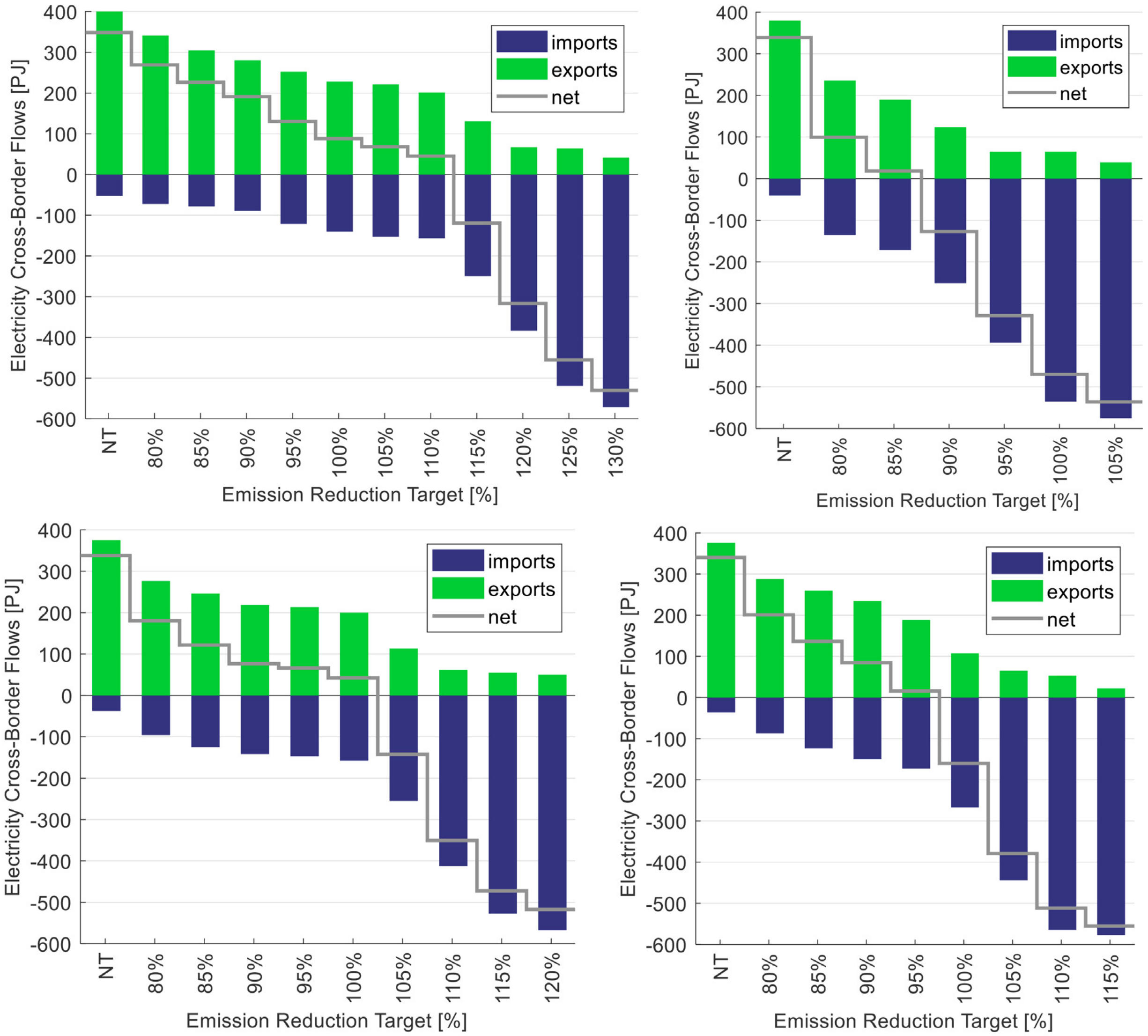

Fig. 21. Import and export electricity flows in 2050 for the four scenarios with different emission targets. Top left: HCHB scenario. Top right: LCLB scenario. Bottom left: LCHB scenario. Bottom right: HCLB scenario.

Table 9
Scenario descriptions for the sensitivity analysis of oil demand streams.

Scenario	Description	Total available biomass [PJ]	Total available biofuels [PJ]	National emission-reduction target [%]	International transport emission reduction target [%]	OBPs for feedstock in petrochemicals [PJ]	OBPs exports [PJ]
S_0	No added policy	1246	750	95	No Target	Unconstrained	3535
S_1	GHG reduction in international transport	1246	750	95	95	Unconstrained	3535
S_2	Ban on oil-based processes for petrochemical sector	1246	750	95	No Target	0	3535
S_3	Assumed elimination of OBP exports	1246	750	95	No Target	Unconstrained	0
S_4	All of the above	1246	750	95	95	0	0

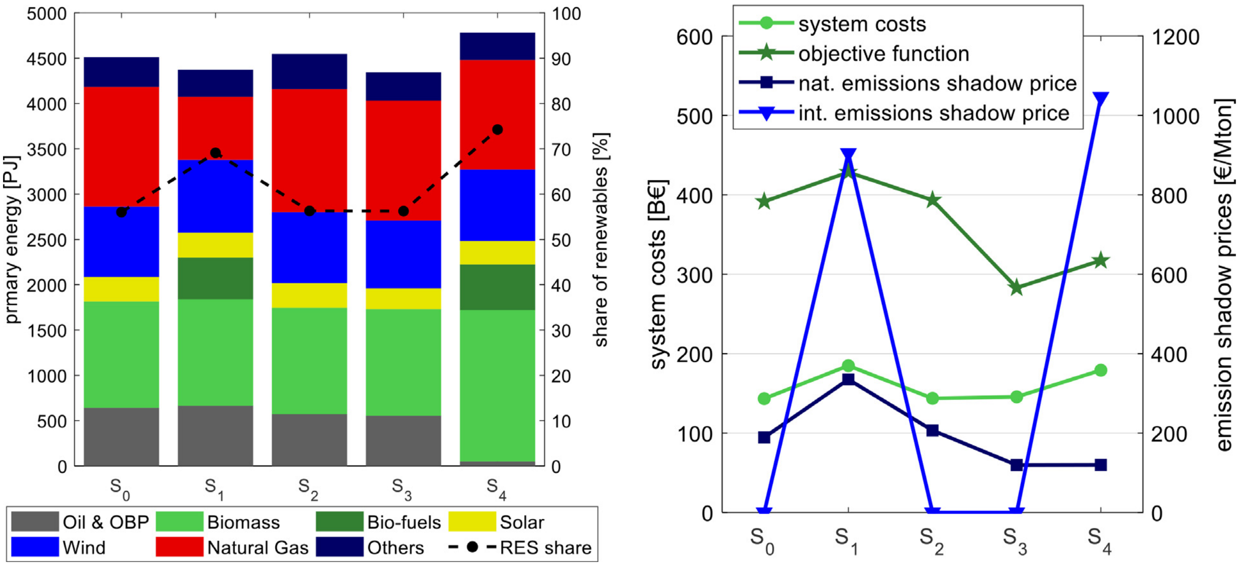

Fig. 22. Sensitivity of the four sensitivity cases of oil demand streams. Left: Primary energy mix in 2050. Right: System costs and emission shadow prices.

For these scenarios, it was necessary to increase the biomass availability to ensure that sufficient biomass was available for use as feedstock in the petrochemical sector. For this, in addition to the 246 PJ of national available biomass, a maximum constraint of 1000 PJ was imposed on imported biomass. In addition, to enable sufficient availability of biofuels for international transport, the maximum constraint was increased to 250 PJ for bio-kerosene and 500 PJ for biodiesel.

The results of these sensitivity runs are presented in Fig. 22, which shows the primary energy mix, system costs, and emission shadow prices. This figure shows that, irrespective of the scenario, the system uses all the available biomass. Furthermore, the system adopts bio-based feedstock extensively (76% of the feedstock comes from biomass in scenario S_o, and 67% in scenario S_3), which indicates that obtaining olefins from wood is close to cost optimality with an ETS emission price of 160 €/ton of CO_2 and an imported wood price of 16.91 €/GJ. It is also interesting to observe that, to (almost) completely eliminate oil use, it is necessary that the export of refined OBPs be eliminated while simultaneously setting a carbon policy on international transport emissions. If only one of the two occurs, OBPs are still a cost-effective alternative for the system, either as feedstock, as fuel for refineries exporting oil, or as kerosene for aviation. Finally, the adoption of natural gas in the mix is strongly influenced by the adoption of oil, as can be observed in scenario S_4, wherein the avoided emissions from OBPs increase the emissions budget and therefore the use of gas-fuelled applications (such as natural gas-powered combined-cycle gas turbines for power generation).

Fig. 22 shows that, from the perspective of cost, it is the international transport emissions policy what affects the objective function, the national system costs, and the national CO_2 shadow price the most. Significant increase in costs occurs only in scenarios wherein the international transport emissions are constrained. The other two elements of the analysis mostly resulted in the reconfiguration of the resources without strongly affecting system costs. This figure is a good method of explaining the difference between the objective function and the Netherlands' system cost. It can be observed that the objective functions of scenarios S_3 and S_4 (where there are no exports of OBPs) are considerably lower than those of the other scenarios. This happens because the disappearance of such considerable energy streams releases the objective function of a significant cost burden. However, the system costs of scenarios S_0 and S_3 are almost equivalent, where the only difference between them corresponds to the part of the export revenues that is lost due to the transformation added value[20] (approximately B€ 2). In addition, scenarios S_3 and S_4 report lower CO_2 shadow prices, which is explained by the avoided emissions from uncaptured GHG at refineries.

It is important to mention that, although power-to-liquids are present in the model, the technologies that are taken into consideration produce primarily road fuels and partially kerosene and residual oil products. It is necessary to include more technologies that can convert captured CO_2 to different forms of hydrocarbons using electricity. These technologies could reduce the biomass required by the system to fully displace OBPs and contribute to the easy and cheap integration of VRES.

4.3. *Impact of biomass resources availability*

The last two exercises presented in Sections 0 and 0 are clear examples of the importance of biomass for energy transition. However, real availability and costs are important uncertainties for an energy system. Therefore, we prepared a bi-dimensional sensitivity analysis of imported biomass while focusing precisely on availability and costs. For this, the sensitivity is built over the same reference scenario presented in Section 0 and comprises 72 scenario runs for eight values of imported biomass prices ranging from 4 to 48 €/GJ and nine values of biomass availability ranging from 0 to 1950 PJ/year.

The main results of these exercises are presented in Fig. 23, where it is shown that biomass (imports) can help to significantly reduce the system costs for the Netherlands. In the extreme case, wherein imported biomass has a high availability (1950 PJ/year) at a very low price (4€/GJ), the objective function can decrease to 9% as compared to the extreme cases wherein there is no imported biomass available or it is extremely expensive (48 €/GJ). It should also be noted that, for this extreme scenario, the CO_2 shadow price approaches zero, indicating that an enforced clean energy system is almost as affordable as an unregulated energy system. For the "conservative area" of the graph, assuming 300 to 600 PJ/year of available biomass and prices between 12 and 20 €/GJ, the impact in the system was found to be significantly sensitive to these values.. In this region, we can find cost reductions of 0.2–0.5% and CO_2 shadow price reductions of 30 €/ton per 100 PJ of extra available imported biomass.

In terms of usage, the results are aligned with the expectations: there is a higher use of biomass when there is more biomass available and when this biomass is cheaper, as shown in Fig. 24. However, a more

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[20] This added value emerges from the energy cost perspective, and it fully neglects the commercial aspects behind the real revenues of energy exports.

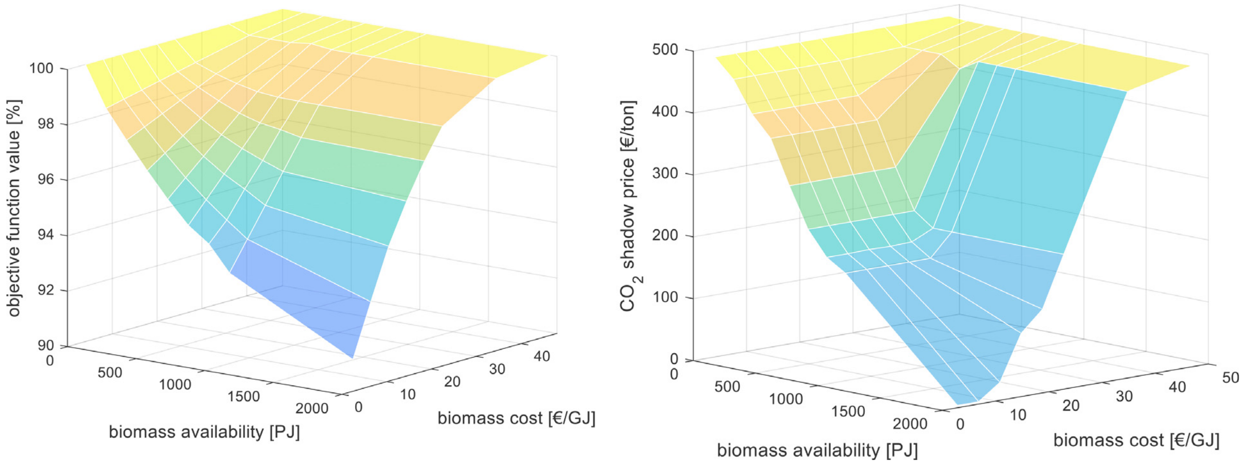

Fig. 23. Impact of the imported biomass availability and its price on the transition costs for the Netherlands energy system. Left: Objective function (i.e. the national system costs, plus the operational costs of the European power system, plus the import costs and export revenues of other energy carriers for the Netherlands). Right: shadow price of emitted CO_2.

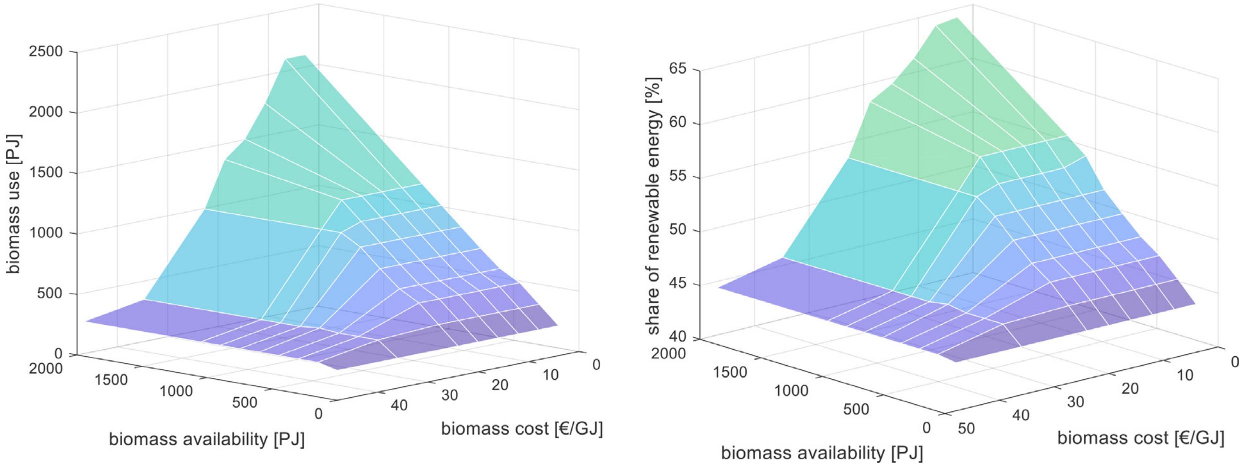

Fig. 24. Impact of the imported biomass availability and its price on the total usage of biomass (left) and share of renewable energy in the primary energy mix (right).

interesting result is that there is an apparent minimum and maximum share of renewable energy in the primary mix in which these sensitivity scenarios move. For instance, when there is no biomass available or when it is available at high costs, the renewable energy share in the mix remains at 45%, and when there is a lot of biomass available at a very low price, the share in the mix increases to 65%.

It is important to clarify that the biomass in this study is considered as a renewable energy source with zero GHG emissions. The role of biomass as an alternative to aid in achieving deep system decarbonisation affordably would decrease if life-cycle emissions are accounted for, thus resulting in an emission-reduction potential of less than 100%. In addition, the availability of biomass for energy is strongly dependant on the food system and agricultural practices; hence, assuming high availability potentials neglects the competition for land between food and energy and most likely represents an unfeasible scenario.

4.4. Sensitivity of 2050 demand drivers in key sectoral activities

A key input required by the model that can strongly influence the model outcome is the assumed demand levels for different system activities. These assumptions play an even more important role after the coronavirus pandemic raised uncertainties around the expected development of different activities in the future economy. Therefore, we include a sensitivity analysis for the demand levels of the different activities within the different driver sectors, as shown in Table 10.

The impact of the demand volumes for each level is presented in Fig. 25, which shows the change in the objective function with respect to the change in demand for each sector. Here, it is shown that both the transport and industrial sectors have the largest impact on the system, where respective changes of 4% and 2% in the objective function are observed when their demand increases or decreases by 20%. However, changes in the demand for activities within the agriculture sector and other emissions yield barely noticeable effects.

However, the fact that changes in a scenario do not result in significant changes in the objective function does not necessarily mean that the system configuration is not affected. Therefore, one of the most important advantages of using an integrated ESM with such a high level of granularity is that it allows us to track changes in other sectors, making it possible to identify possible cross-sectoral feedbacks. Fig. 26 presents the impact that the demand deviations have on the sectoral costs of the most affected sectors.

Firstly, in the case of the industry sector (subfigure A), it can be observed that the demand deviations present a feedback proportional with the renewable, fossil, and final gas sectors, while it presents a negative feedback with refineries and subsequently hydrogen sectors. This increase in the required feedstock materials results in an increase in secondary refined products, which leads to a decrease in the production

Table 10
Description of the scenarios used for the sensitivity analysis presented in section 0.

Sector	Activity	Units	Value in 2050				
			Reference	−20%	−10%	10%	20%
Agriculture	Electricity demand	[PJ]	47	37.6	42.3	51.7	56.4
Agriculture	Heat demand horticulture	[PJ]	101.5	81.2	91.35	111.65	121.8
Agriculture	Heat demand other	[PJ]	9.6	7.68	8.64	10.56	11.52
Agriculture	Machinery	[PJ]	30.2	24.16	27.18	33.22	36.24
Industry	Steel production	[Mton_Steel]	7.27	5.82	6.54	8	8.72
Industry	Non-ferrous production	[Mton_Al]	0.2	0.16	0.18	0.22	0.24
Industry	Ammonia production	[Mton_NH3]	3.35	2.68	3.02	3.69	4.02
Industry	Petrochemical transformation	[Mton_HVC]	8.7	6.96	7.83	9.57	10.44
Industry	Other ETS chemicals	[Idx_2020]	1.55	1.24	1.4	1.71	1.86
Industry	Other ETS	[Idx_2020]	1.13	0.9	1.01	1.24	1.35
Industry	Other non-ETS	[Idx_2020]	1	0.8	0.9	1.1	1.2
Industry	Machinery	[PJ]	49.5	39.6	44.55	54.45	59.4
Transport	Motorcycles	[Gvkm]	7.2	5.76	6.48	7.92	8.64
Transport	Passenger cars	[Gvkm]	125.3	100.24	112.77	137.83	150.36
Transport	Light-duty vehicles	[Gvkm]	32.3	25.84	29.07	35.53	38.76
Transport	Heavy-duty vehicles	[Gvkm]	8.25	6.6	7.43	9.08	9.9
Transport	Buses	[Mvkm]	650	520	585	715	780
Transport	Rail	[Mvkm]	230	184	207	253	276
Transport	Intra-EU aviation	[Mvkm]	430	344	387	473	516
Transport	Extra-EU aviation	[Mvkm]	850	680	765	935	1020
Transport	Inland-domestic navigation	[Mvkm]	90	72	81	99	108
Transport	International navigation	[Mvkm]	145	116	130.5	159.5	174
Transport	Other transport	[PJ]	30	24	27	33	36
Other emissions	CH_4 enteric fermentation	[Mton_CO2]	6.88	5.5	6.19	7.57	8.26
Other emissions	CH_4 manure management	[Mton_CO2]	3.22	2.57	2.9	3.54	3.86
Other emissions	N_2O manure management	[Mton_CO2]	0.65	0.52	0.59	0.72	0.78
Other emissions	N_2O Fertiliser	[Mton_CO2]	2.7	2.16	2.43	2.97	3.24
Other emissions	HFC Refrigeration	[Mton_CO2]	1.5	1.2	1.35	1.65	1.8
Other emissions	CO_2 others	[Mton_CO2]	2.2	1.76	1.98	2.42	2.64
Other emissions	CH_4 others	[Mton_CO2]	0.25	0.2	0.23	0.28	0.30
Other emissions	N_2O others	[Mton_CO2]	2	1.6	1.8	2.2	2.40
Other emissions	F-gas others	[Mton_CO2]	0.2	0.16	0.18	0.22	0.24

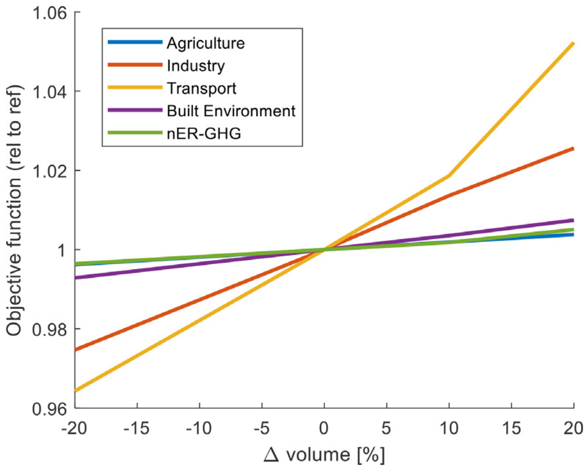

Fig. 25. Behaviour of the objective function as a response to changes in 2050 demand of activities in some sectors of the system.

of electric fuels. Different results may arise if the model is equipped with technologies capable of producing ethylene and other petrochemical supplies from hydrogen or electricity.

Secondly, changes in the transport sector (subfigure B) result in proportional feedbacks in the renewables, fossil, and final gas sectors. However, an interesting observation can be made in the case of refineries, which, owing to a substitution to oil refining from synfuel production, first presents a decrease and then an increase in the sector costs. Moreover, owing to an increase in non-ETS emissions when the transport demand increases by 20%, the residential and services sectors adopt district heating, thus increasing the sectoral costs of the heat networks.

Thirdly, the change in other emissions volumes (subfigure C) produces a substitution from fossil fuels to renewable energies. This change explains the trends in such sectors as well as the barely noticeable change in its “competing” non-ETS sector costs (namely, transport and residential sectors).

Finally, in the agriculture sector (subfigure D), lesser fossil fuels are used for machinery when the demand increases. This results in a lesser use of hydrogen in the system owing to the decreased use of synfuels, which explains the inverse feedback behaviour for this interaction. Moreover, the changes in the built environment demand appear to have negligible propagation effects on other sectors, as the changes are only apparent in the residential and services sectors.

5. Discussion

To obtain all the above results, many runs were required, which consumed a significant amount of computational time. The main model run that produced the results presented in Section 0, which optimises the operation and planning for the period between 2020 and 2050 in five-year intervals with perfect foresight required under 6 h on a computer using a six-core processor, 32 GB of RAM, and an unblocked solid state drive. For the sensitivity analyses, the problem was solved only for the year 2050 to make it possible to collect a large number of data points, as a single-year run requires 20–30 min. However, this means that over 60 h of computational time was required to produce the 132 scenario cases used for the different sensitivity analyses. For each of these runs, the model was able to represent the electricity despatch of the European power system and the cross-sectoral flexibility technologies that contribute to adopting higher levels of VRES simultaneously with the capacity planning of the system for the year 2050, using a complete energy system representation that accounts for all emission forms in every sector. These sensitivity exercises are perfect and practical examples

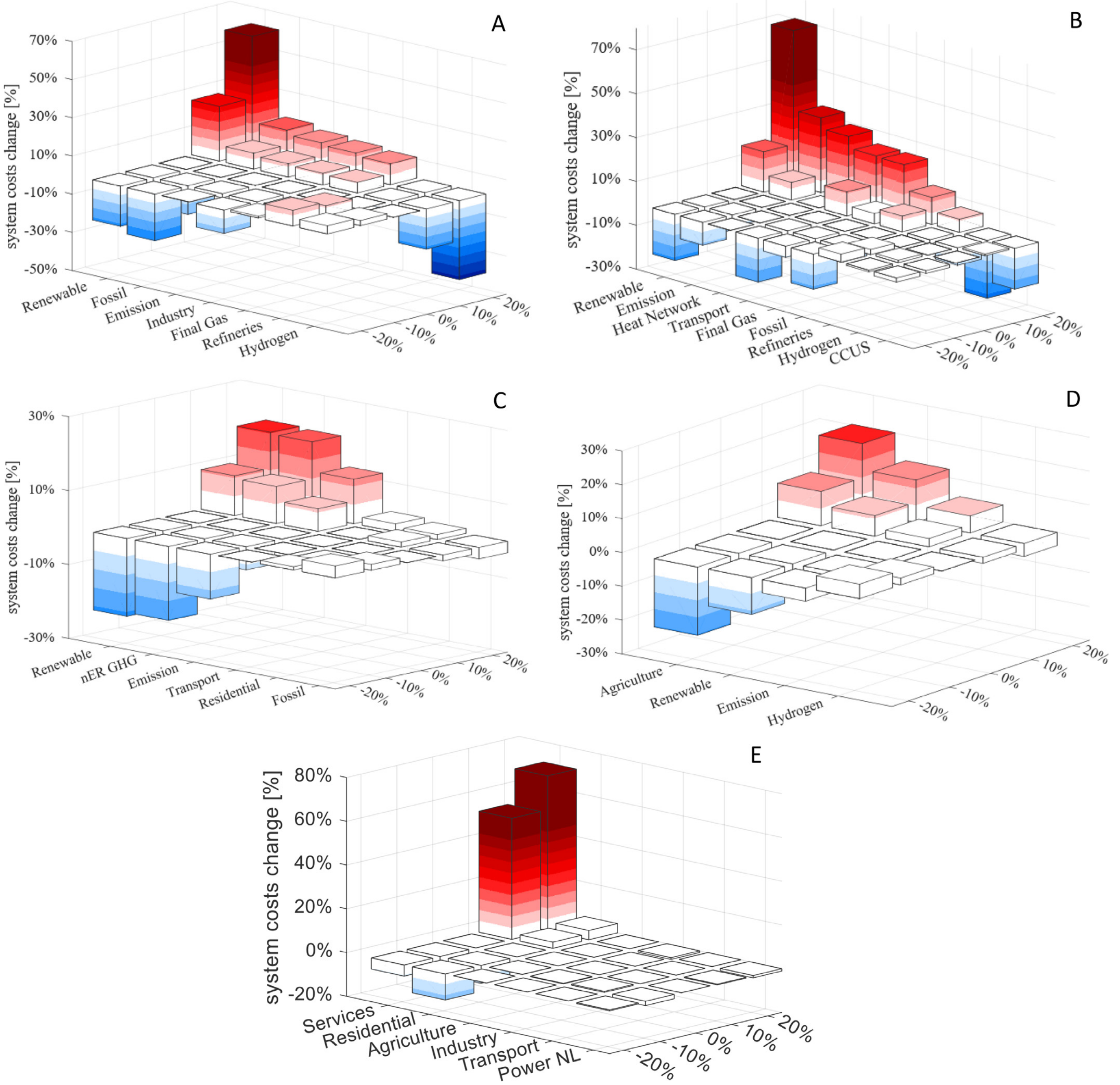

Fig. 26. Changes in sectoral costs for different demand deviations for industry (A), transport (B), other emissions (C), agriculture (D), and built environment (E).

to explain why IESA-Opt also presents a significant methodological improvement, as its computational agility opens up new possibilities.

IESA-Opt is suitable for many stand-alone applications, such as for exploring the role of public subsidies to achieve decarbonisation targets; determining future possible load profiles for the system owing to the influence of EVs, electric heating, industrial transformation, and cross-sectoral flexibility technologies; the effect of uncertain demand projection in system costs and emissions reduction targets; and specific sectoral analysis to identify ideal operational planning and optimal technology choices amongst several possible options. Furthermore, under the IESA framework depicted in Fig. 1, this model can be used in collaboration with other models or under specific adaptations of its methodology for application in broader studies, such as a collaboration with macroeconomic models to quantify the feedbacks between the energy transition and GPD or employment; identification of national and regional constraints imposed by spatially sensitive parameters with the aid of spatial models and tools; and integration with agent-based simulation models for measuring the deviation between behavioural trends and social optima and the role of policy toolboxes in mitigating such deviations.

Nevertheless, it is important to mention that both the model and the analysis present some limitations. Firstly, wind energy is the largest share of the 2050 energy mix, relying mostly on offshore wind power generation. However, this analysis describes offshore wind as a single technology without considering different cost profiles based on spatial potentials, this can affect both the Netherlands and the North Sea power despatch considerably, as well as the costs of the transition [57]. Secondly, we adopted an LP formulation, which does not take into consideration the unit commitment (MILP) for describing the operation of thermal generators. Secondly, we did not model reserves in the power sector, which can affect the outcome of the system configuration and thus the transition costs. Similarly, we assumed perfect foresight for modelling the energy transition, and thus, no forecasting errors were included in the operation profile predictions. This is another source of extra transition costs when dealing with large amounts of VRES in the system. In addition, for this analysis, we only used one climate year for all the VRES availability profiles in the whole transition; thus, we neglected the impact of climate change on resource availability and the different operation settings that the system might confront. Furthermore, the technological description is not yet fully extensive, as industrial activities should be further disaggregated to account for more decarbonisation technologies and further cross-sectoral synergies (e.g. mode-flexible processes such as smelters, paper mills, and local waste heat-recirculation networks). Finally, technological costs are exogenous, and thus, the model cannot account for the negative feedback from technological learning if investments are postponed until the last part of the transition. Therefore, the technology cost descriptions are a key component of the scenario definition, and owing to the extensive portfolio of options, there is no sensitivity analysis included in this study to address this issue.

To address some of these limitations and expand the reach of the possible analyses, there is a list of further improvements that can be made to the model. Firstly, we intend to focus on increasing the resolution with respect to industrial activities' descriptions. In addition, we are already expanding the geographical scope of the model by including all the countries around the North Sea to better account for European flexibility, offshore installations, and hydrogen development paths. We also intend to link the model with a macroeconomic module to account for important feedbacks with the economy, such as prices of commodities' prices and demand volumes. It is also important to mention that, given the wide energy system definition of IESA-Opt, it is sensitive to the data quality fed into the model ;[21] hence, collecting, managing, and maintaining the database comprises a process of continuous improvement. This expands the scope for improvement and opens the door for other potential future research efforts. For instance, currently, the available data of the hourly demands of certain technologies are too generic (e.g. standard load, day and night, and flat profiles are applied to many technologies owing to the lack of available data) and could be improved, which could yield interesting studies on the evolution of demand profiles in the transition. Furthermore, the EV technologies and infrastructure catalogue could be expanded to compare the cost-effectiveness of options.

6. Conclusion

IESA-Opt is an adequate tool for analysing the impact of cross-sectoral flexibility in an integrated energy system in the Netherlands, which helps in understanding ways to further accommodate large amounts of variable renewable electricity. As an evidence of this, IESA-Opt was applied in this case study to determine the behaviour of energy system transition when taking into consideration interactions in terms of energy usage, emissions, and costs, while considering intra-year dynamics of the despatch and operation of the power despatch, gaseous networks, and cross-sectoral flexibility. Following are the two most relevant highlights of these results: 1) even in a high decarbonisation scenario, fossil fuels remain largely used as many causal factors such as international transport, exports of refined products, and industrial feedstock are not included in current climate policies in the Netherlands; 2) there will be a pivotal switchfrom fuel costs to capital costs in the energy transition that is mainly driven by electrification and the adoption of "fuel-less" renewable energy sources and technologies that can provide cross-sectoral flexibility.

In addition, several sensitivity analyses were performed to highlight the critical role of biomass and CCUS in achieving negative emissions to highlight the importance of including different demand streams for oil in the climate policy packages and to quantify the uncertainty of key demand volumes for different sectors. From these, the most significant learning is that in order to displace oil-based products from the energy mix, a policy package comprising international transport, feedstock for high-value chemicals, and refined oil products exports is required in top of the current emission reduction targets. However, to make this transition affordable and effective it is necessary to ensure the availability of biomass resources together with the development of carbon capture and storage technologies. These findings are very relevant to help guiding the energy transition and are worthy to further exploration by means of further expansion of IESA-Opt capabilities as well as by the linking of the model with other analytical tools.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.adapen.2021.100043.

Appendix

Appendix A. Multi criteria analysis on the ESMs comparison

The Multi-Criteria Analysis

Considering the criteria regarding the future low-carbon energy systems and available models, it can be concluded that no perfect model exists. Models can be assessed based on the list of criteria such as temporal resolution, spatial resolution, the social aspect, data source quality, accessibility, and application (Table 11).

The capability of the model in each criterion is given a score from five (highest) to one (lowest) as presented in

Table 12. The results are highly dependant on the scores and weights, which are both - to some extent - subjective. Readers can alter the results by incorporating new criteria or changing the perspective weights. In the following sections, these modelling capabilities and the corresponding scores are explained.

Technological detail and learning

There are two parameters that differ across integrated ESMs, which are the inclusion of FOs and the inclusion of technological learning. Therefore, models can be grouped into three groups: (i) no flexibility option and no technological learning that would score one; (ii) the inclusion of either flexibility options or technological learning that would

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[21] The complete model database is available in the online user interface [22].

Table 11
The need for certain modelling capabilities results in several assessment criteria.

Capabilities	Criteria
Flexibility options (Storage, DSM, Curtailment, Conventional generation, Cross border trade) Seasonal Storage (PHES, CAES, TES, HES) Sectoral coupling technologies (P2Mobility, P2Heat, P2Gas) The granularity of presented technologies (current basket of technologies, P2X family, new renewable sources, and storage options) Technological learning (exogenous, 1-factor endogenous, multi-factorendogenous, MCL, MRL)	Technological detail and learning
Fine temporal resolution (HTR, HTR time-slices + CO, HTR time-slices)	Temporal resolution
Fine spatial resolution (national, regional, GIS)	Spatial resolution
Human behaviour (agent type, neighbourhood effect, and heterogeneity)	Social parameters
General capabilities	modelling methodology Data use Accessibility and Application

Table 12
Score criterion for different modelling capabilities.

Criteria	Score				
	1	2	3	4	5
Technological detail and learning	No flexibility option and No technological learning		Flexibility options or technological learning		Flexibility options and technological learning
Temporal resolution	More than a year		Hourly time-slices		Hourly temporal resolution
Spatial resolution	Without regional depth			Considering regions	Considering GIS data
social parameters	demand curves				abms
modelling methodology	calculator				non-calculator
Data source	No data	Generalized open-source global data	Limited country-specific data	Detailed open-source global data	Detailed country-specific datasets possibly in combination with global datasets
Accessibility	No access	Limited access	Commercial	Open-source upon request	Open-source and accessible through web
Application	No publication	Applied in one country	Applied in two countries	Applied across EU countries	Applied globally

score three; and (iii) the inclusion of flexibility options and technological learning that would score five.

Temporal resolution

ESMs usually balance the supply and demand on a yearly basis or a limited amount of (hourly) time-slices per year. Nevertheless, some models have a higher temporal resolution and balance the system on an hourly basis. Reviewed models can be categorized in three groups: (i) temporal resolution on yearly basis that would score one; (ii) time-slice approach that would score three; and (iii) hourly temporal resolution that would score five.

Spatial resolution

Some models have the capability to model the regions inside a country. This ability can provide regional insights on energy system policies and vice versa. Although the limited computational capacity and the lack of data make it difficult to perform a detailed regional analysis, some models balance the system in different regions inside the country based on different capacities and properties of the regions (e.g., ESME in the UK). Reviewed models are divided in three groups: (i) models without regional depth that would score one; (ii) models which consider regions that would score four, since it is a considerable improvement; and (iii) models which consider GIS data that would score five.

Social parameters

The role of social analysis in techno-economic models is usually negligible. However, some modelling tools practice multi-agent programming in order to model qualitative aspects of stakeholders' decision-making practice on energy systems. Models are categorized into two groups: (i) models capturing socio-economic parameters only based on demand curves that would score one, and (ii) agent-based models considering a set of decision-making rules for different stakeholders in the energy system that would score five.

Modelling methodology

Reviewed models practice a different set of methodologies. In this review, the main categorization between methodologies can be made between the calculator and non-calculator methodologies. Therefore, models can be grouped into two groups: (i) calculator models that would score one, and (ii) non-calculator models that would score five.

Data use

The depth of technical detail and the quality of the data play a crucial role in providing accurate insights into the energy system with regard to new technologies and sectoral coupling. Moreover, data access is the first limitation of energy system research as databases are rather private. Models can then be divided into five groups: (i) models not indicating a data source that would score one; (ii) models using generalized open-source data that would score two; (iii) models using limited country-specific data that would score three; (iv) models using detailed open-source data that would score four; and (v) models using detailed country-specific datasets, possibly in combination with global datasets that would score five.

Accessibility

Open-access models provide an opportunity to test the model and provide feedback. These models are divided into five groups: (i) models which provide no access that would score one; (ii) models which provide limited access that would score two; (iii) models which are commercial that would score three; (iv) models which are open-source but need permission that would score four, and (v) models which are completely open-source and accessible on Internet that would score five.

Application

A model with more applications and users makes it easier to disseminate and discuss results. Models are grouped in five sets: (i) models with no publication yet that would score one; (ii) models applied in one country that would score two; (iii) models applied in two countries that would score three; (iv) models applied across EU countries that would score four, and (v) models which applied in many countries and are well-known that would score five.

Table 12, Summary of the corresponding scores to modelling capabilities in each criterion. Table 13 demonstrates the MCA analysis with equal weight for all criteria. To calculate the score of each model for each criterion, the weighted percentage of that criteria in the model's total score is demonstrated. This percentage is calculated endogenously, as explained by (1. It indicates the share of the models' score in each criterion out of the models' total score.

$$Weighted\ percentage_{(Model,\ Criterion)} = \frac{Score_{(Model,\ Criterion)} \times Weight_{(Model,\ Criterion)}}{\sum_{c=1}^{c=8} \left(Score_{(Model,\ c)} \times Weight_{(Model,\ c)}\right)} \qquad (1)$$

PRIMES would score high mainly due to the inclusion of social parameters, while the high score of REMix is due to its high spatial resolution. These models merely demonstrate improved capabilities compared to others; therefore, it *does not* mean that these models are "best" models. Moreover, some features of the models are not reflected in this table. For instance, METIS works complementary to long-term ESMs as it only simulates one specific year. Besides, the MCA results can be changed considerably by assigning slightly different scores to various criteria as total scores are relatively close. Models such as the MARKAL family and METIS demonstrate high scores mainly due to their high granularity; however, they lack the inclusion of social parameters. ENSYSI includes social parameters while lacking spatial resolution and application.

Sensitivity analysis

Addressing all the policy-induced challenges of the energy system requires a comprehensive ESM that is not yet available. Therefore, a compromise should be made based on the challenges that the model is designed to address.

Consequently, a weighted decision matrix can be formed by using the AHP method Invalid source specified.. In this method, the criteria are rated against each other with respect to the challenges. A consistency ratio (CR) is calculated to indicate the reliability of the weight table. Saaty suggests that the CRs of more than 0.1 are too inconsistent to be considered reliable Invalid source specified.. Here the challenges are divided into two main groups, first: intermittency, flexibility, and further electrification; and second: human behaviour and decentralization. The first group of challenges puts emphasis on the technological detail, the high temporal and spatial resolution; while the second group emphasizes the inclusion of social parameters and high spatial resolution.

The pair-wise weighted decision matrix for the first group of challenges is formed in Table 14. In each row, the importance of a criterion compared to other criteria is given a number in this order: 1 would be equal importance, 3 would be fairly important, and 5 would be extremely important. It should be noted that these numbers are entirely subjective, thus, the user can make his own decision matrix. Then, the table is normalized and the sum of each row is reported as the weight of the criterion. To calculate the CR, each column of the pair-wise table is multiplied by the corresponding weights. Then, the sum of each row is divided by the corresponding weight to get λ values. The CR is then calculated by equation 2, in which n is the number of criteria.

$$CR = \frac{\lambda_{average} - n}{n - 1} \qquad (2)$$

Table 14, Weighted decision matrix for the first group of challenges-Repeating the same procedure for the second group of challenges leads to the weights presented in Table 15. In both cases, the low CR indicates low levels of inconsistency in the assigned weights.

Table 15, The weight table of two groups of challenges for the MCAUsing the weights in Table A5 to update the MCA will lead to a

Table 13
The MCA analysis table with equal weights.

Model name	Modelling methodology		Technological detail		Temporal resolution		Spatial resolution		Social parameters		Data source		Accessibility		Application		Total
PRIMES	5	15%	5	15%	3	9%	4	12%	5	15%	4	12%	3	9%	4	12%	4.13
REMix	5	15%	5	15%	3	9%	5	15%	1	3%	5	15%	4	12%	5	15%	4.13
MARKAL f.	5	16%	5	16%	3	9%	4	13%	1	3%	4	13%	5	16%	5	16%	4.00
METIS	5	16%	3	10%	5	16%	5	16%	1	3%	4	13%	4	13%	4	13%	3.88
ENSYSI	5	17%	3	10%	5	17%	1	3%	5	17%	5	17%	4	14%	1	3%	3.63
OSeMOSYS	5	18%	5	18%	3	11%	4	14%	1	4%	2	7%	5	18%	3	11%	3.50
OPERA	5	19%	5	19%	3	12%	1	4%	1	4%	5	19%	4	15%	2	8%	3.25
NEMS	5	19%	5	19%	1	4%	4	15%	1	4%	4	15%	4	15%	2	8%	3.25
POLES	5	19%	5	19%	1	4%	4	15%	1	4%	4	15%	2	8%	4	15%	3.25
SimREN	5	19%	3	12%	5	19%	4	15%	1	4%	5	19%	1	4%	2	8%	3.25
EnergyPLAN	1	4%	3	12%	5	20%	1	4%	1	4%	5	20%	5	20%	4	16%	3.13
ESME	5	21%	3	13%	3	13%	4	17%	1	4%	5	21%	1	4%	2	8%	3.00
IWES	5	21%	3	13%	5	21%	4	17%	1	4%	3	13%	1	4%	2	8%	3.00
STREAM	1	4%	3	13%	5	22%	4	17%	1	4%	2	9%	5	22%	2	9%	2.88
ETM	1	5%	3	16%	5	26%	1	5%	1	5%	2	11%	4	21%	2	11%	2.38
LEAP	1	5%	1	5%	1	5%	4	21%	1	5%	4	21%	3	16%	4	21%	2.38
E4Cast	5	28%	1	6%	1	6%	4	22%	1	6%	3	17%	1	6%	2	11%	2.25
DynEMo	1	6%	3	18%	5	29%	1	6%	1	6%	1	6%	2	12%	3	18%	2.13
IKARUS	5	29%	1	6%	1	6%	1	6%	1	6%	5	29%	1	6%	2	12%	2.13
Weights	1		1		1		1		1		1		1		1		8

Note: Percentages may not add up to 100 due to rounding.

Table 14
Table with the pair-wise weighted decision matrix.

cr = 0.05	Modelling methodology	Technological detail	Temporal resolution	Spatial resolution	Social parameters	Data source	Accessibility	Application	Weight
Modelling methodology	1	1/3	1/5	1/2	3	1/2	1	1	0.07
Technological detail	3	1	1/2	3	5	3	4	4	0.23
Temporal resolution	5	2	1	3	5	3	5	5	0.30
Spatial resolution	2	1/3	1/3	1	4	2	4	4	0.15
Social parameters	1/3	1/5	1/5	1/4	1	1/3	1/2	1/2	0.04
Data source	2	1/3	1/3	1/2	3	1	3	3	0.11
Accessibility	1	1/4	1/5	1/4	2	1/3	1	2	0.06
Application	1	1/4	1/5	1/4	2	1/3	1/2	1	0.05
Sum	15.33	4.70	2.97	8.75	25.00	10.50	19.00	20.50	1

Table 15
.Weights used for the decision matrix.

Challenges	Modelling methodology	Technological detail	Temporal resolution	Spatial resolution	Social parameters	Data source	Accessibility	Application	CR
Intermittency, flexibility, and further electrification	0.07	0.23	0.3	0.15	0.04	0.11	0.06	0.05	0.05
Human behaviour and decentralization	0.05	0.11	0.13	0.19	0.33	0.09	0.06	0.04	0.06

Table 16
Changes in the MCA analysis table based on perspective weights.

Equal weights	First group perspective	Second group perspective
REMix	REMix	PRIMES
PRIMES	METIS	ENSYSI
MARKAL f.	MARKAL f.	REMix
METIS	PRIMES	METIS
ENSYSI	SimREN	MARKAL f.
OSeMOSYS	ENSYSI	SimREN
SimREN	OSeMOSYS	OSeMOSYS
NEMS	IWES	IWES
POLES	STREAM	NEMS
OPERA	EnergyPLAN	STREAM
EnergyPLAN	OPERA	POLES
IWES	ESME	ESME
ESME	NEMS	OPERA
STREAM	POLES	EnergyPLAN
ETM	ETM	LEAP
LEAP	DynEMo	ETM
E4Cast	LEAP	E4Cast
DynEMo	E4Cast	DynEMo
IKARUS	IKARUS	IKARUS

slightly different model ranking, presented in Table 16. For the first group, it is expected that models with high scores in technological detail, temporal resolution, and spatial resolution will get higher total scores. The REMix model gets a high total score mainly due to the inclusion of high spatial resolution with the use of GIS data and the inclusion of key flexibility and storage technologies with the exogenous technological learning. The METIS model provides lower technological detail by neglecting technological learning while incorporating hourly temporal resolution and GIS-based spatial resolution. For the second group, the inclusion of social parameters and fine spatial resolution gains importance. Models with the inclusion of social parameters such as PRIMES and ENSYSI get higher scores. Although the METIS model does not include social parameters, it keeps a high score due to its fine spatial resolution.

Irrespective of the assigned weights, we find four models at the top of the MCA table which are REMix, PRIMES, METIS, and the MARKAL family models. These models had high scores in nearly all criteria, while a low score in one criterion (for instance, lack of social parameters for REMix) is compensated with a high score in other criteria (high temporal and spatial resolution). These four models were either developed recently (e.g., REMix and METIS) or are under constant development (e.g., MARKAL family and PRIMES). It shows how integrated energy system modelling points towards the models with improved capabilities in all the criteria.

Other models keep the same ranking position except for IWES, ENSYSI, and EnergyPLAN, which changed their position considerably (i.e., more than two steps change). This position change can be explained by the asymmetry of these models' scores in the MCA table. For instance, the IWES model gets a high score in the first four criteria while getting a low score in the last four criteria.

The MCA represents an overview of the current state of ESMs with regard to low-carbon energy system modelling challenges. However, there is a need for adding new capabilities to current ESMs in order to address future modelling challenges. In the next section, we discuss two potential modelling solutions based on our observation from the current state. The overall solution is to expand single models and/or to link different models.

Appendix B. Energy System representation in IESA-Opt

In Table 17 we provide the representation of the energy system considered in IESA-Opt. Here you can find all the technologies able to satisfy the demand of each activity considered in the model. There are three types of activities: driver activities, energy activities, and emission activities. The driver activities create the energy requirements which are satisfied by the energy activities. The operation of both activities result in emissions which are accounted by emission activities. The energy system is divided in 7 sectors for the driver activities: Residential, Services, Agriculture, Industry, Transport, EU Power System, and Non-Energy Related Emissions. The energy activities are segregated in: Power, Refineries, Natural Gas, Hydrogen, District Heating and Final Biomass sectors.

Appendix C. Model formulation

C.1. Sectoral integrated cost-optimized energy system towards decarbonization targets

As described in the above presented conceptual framework, sectoral integration in IESA-Opt turns around two main axes, activities and technologies (analogously to the commodities and processes nomenclature

Table 17
Energy System representation in IESA-Opt.

Activity	Sector	Type	List of technologies
Electricity demand - Residential	Residential	Driver	Demand
Houses - Residential Flats	Residential	Driver	House with insulation GFE, House with insulation DC, House with insulation B, House with insulation A, House with insulation *A+*
Houses - Residential Terrace	Residential	Driver	
Houses - Residential Dwellings	Residential	Driver	
Heat LT Houses C-G	Residential	Energy	Boiler Gas, District Heating
Heat LT Houses A,B	Residential	Energy	Boiler Gas, District Heating, Hybrid Heat Pump
Heat LT Houses *A+*	Residential	Energy	Boiler Gas, Boiler Gas wSolar, District Heating, Hybrid Heat Pump, Electric Heater, Electric Heater wSolar, Electric Heat Pump Air, Electric Heat Pump Air FLEX, Electric Heat Pump GW, Electric Heat Pump GW FLEX, Micro CHP Gas, Micro CHP H2
Electricity demand - Services	Services	Driver	Demand
Space - Services	Services	Driver	Space with insulation GFE, Space with insulation DC, Space with insulation B, Space with insulation A, Space with insulation *A+*
Heat LT Services	Services	Energy	Boiler Gas Standard, Boiler Gas HR107, Hybrid Heat Pump, Electric Heat Pump Air, Electric Heat Pump Soil, Mini CHP Gas, CHP H2
Electricity demand - Agriculture	Agriculture	Driver	Demand
Heat demand - Agriculture Horticulture	Agriculture	Driver	Demand
Heat demand - Agriculture Other	Agriculture	Driver	Demand
Machinery - Agriculture	Agriculture	Driver	Fuel based machinery, Hybrid machinery
Heat LT Agriculture Horticulture	Agriculture	Energy	CHP Gas, Boiler Gas, Geothermal HP, Shallow Soil Energy, Boiler Biomass
Heat LT Agriculture Other	Agriculture	Energy	Co-Digestion Biomass, Boiler Gas
Steel production - Basic Metals Industry	Industry	Driver	Blast Furnace, Blast Furnace wCCS, Hisarna, Hisarna wCCS, ULCOWIN
Non-Ferro production - Basic Metals Industry	Industry	Driver	Hall-Heroult Standard, Hall-Heroult Improved, Hall-Heroult Novel
Ammonia production - Fertilizer Industry	Industry	Driver	Haber Bosch, Haber Bosch wCCS, Haber Bosch New, Haber Bosch New wCCS, Solid State Ammonia Synthesis (SSAS)
High-value chemicals - Chemical Industry	Industry	Driver	Nafta Steam Cracker Standard, Nafta Steam Cracker Standard wCCS, Naphtha Steam Cracker Improved, Naphtha Steam Cracker Improved wCCS, Olefins from Sugar, Olefins from Starch, Olefins from Wood

(*continued on next page*)

Table 17 (*continued*)

Activity	Sector	Type	List of technologies
Other ETS chemicals - Chemical Industry	Industry	Driver	Remaining Chemicals Production Standard, Remaining Chemicals Production Improved
Other ETS - Industry	Industry	Driver	Remaining ETS Industry Standard, Remaining ETS Industry Improved
Other non-ETS - Industry	Industry	Driver	Remaining non-ETS Industry Standard, Remaining non-ETS Industry Improved
Machinery - Industry	Industry	Driver	Fuel based machinery, Hybrid machinery, Electric machinery
Waste Incineration	Industry	Driver	CHP Waste, CHP Waste wCCS
Waste Sewage	Industry	Driver	CHP after gasification of Sewage
Waste Landfill	Industry	Driver	Gasification of Landfill
Heat SHT Industry	Industry	Energy	Boiler Gas, Boiler Gas wCCS, Hybrid Boiler Gas, Hybrid Boiler Gas wCCS, Boiler Coal, Boiler Coal wCCS, Boiler Biomass, Boiler Biomass wCCS, Boiler H2
Heat HT Industry	Industry	Energy	Boiler Gas, Boiler Gas wCCS, Hybrid Boiler Gas, Hybrid Boiler Gas wCCS, Boiler Coal, Boiler Coal wCCS, Boiler Biomass, Boiler Biomass wCCS, CHP Gas, CHP Gas wCCS, CHP Biomass (S), CHP Biomass (S) wCCS, CHP Biomass (L), CHP Biomass (L) wCCS, Boiler H2
Heat LT Industry	Industry	Energy	Boiler Gas, Boiler Gas wCCS, Boiler Coal, Boiler Coal wCCS, Boiler Biomass, Boiler Biomass wCCS, Heat Pump Gas, Heat Pump Electricity, Geothermal HP, Boiler H2, Direct Heating Electricity, Co-Digestion Biomass
Motorcycles	Transport	Driver	ICE Vehicle, Electric Battery Vehicle
Passenger Cars	Transport	Driver	ICE 2010 norm Vehicle, ICE 130 g Vehicle, ICE 95 g Vehicle, ICE 70 g Vehicle, ICE Hybrid Vehicle, ICE Natural Gas Vehicle, Plug-In Hybrid Vehicle, Electric Battery Vehicle, Electric Battery Vehicle FLEX, Electric Battery Vehicle P2G, Hydrogen Fuel Cell Vehicle
Light-Duty Vehicles	Transport	Driver	ICE 2010 norm Vehicle, ICE 175 g Vehicle, ICE 147 g Vehicle, ICE 114 g Vehicle, Plug-In Hybrid Vehicle, Electric Battery Vehicle, Electric Battery Vehicle FLEX, Hydrogen Fuel Cell Vehicle
Heavy-Duty Vehicles	Transport	Driver	ICE 2010 norm Vehicle, ICE efficient Vehicle, ICE Natural Gas Vehicle, Electric Battery Vehicle, Electric Battery Vehicle FLEX, Hydrogen Fuel Cell Vehicle

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Table 17 (*continued*)

Activity	Sector	Type	List of technologies
Buses	Transport	Driver	ICE Vehicle, ICE Vehicle Natural Gas, Plug-In Hybrid Vehicle, Electric Battery Vehicle, Hydrogen Fuel Cell Vehicle
Rail	Transport	Driver	Compression Ignition Train, Conventional Electric Train
Intra-EU Aviation	Transport	Driver	Conventional aeroplane
Extra-EU Aviation	Transport	Driver	
Inland-Domestic Navigation	Transport	Driver	Heavy Oil Ship, ICE Ship,
International Navigation	Transport	Driver	CNG Ship
nER-GHG Agriculture - CH4 Enteric Fermentation	Other Emissions	Driver	Enteric Fermentation CH4 Emissions
nER-GHG Agriculture - CH4 Manure Management	Other Emissions	Driver	Manure Management CH4 Emissions
nER-GHG Agriculture - N2O Manure Management	Other Emissions	Driver	Manure Management N2O Emissions
nER-GHG Agriculture - N2O Fertilizer	Other Emissions	Driver	Fertilizer N2O Emissions
nER-GHG Product Use - F-gas Refrigeration	Other Emissions	Driver	Refrigeration HFCs Emissions
nER-GHG All - CO2 Others	Other Emissions	Driver	Other CO2 Emissions
nER-GHG All - CH4 Others	Other Emissions	Driver	Other CH4 Emissions
nER-GHG All - N2O Others	Other Emissions	Driver	Other N2O Emissions
nER-GHG All - F-gas Others	Other Emissions	Driver	Other F-gas Emissions
Electricity demand - BN	EU Power System	Driver	Demand
Electricity demand - BU	EU Power System	Driver	Demand
Electricity demand - BT	EU Power System	Driver	Demand
Electricity demand - FI	EU Power System	Driver	Demand
Electricity demand - IT	EU Power System	Driver	Demand
Electricity demand - PT	EU Power System	Driver	Demand
Electricity demand - ES	EU Power System	Driver	Demand
Electricity demand - SK	EU Power System	Driver	Demand
Electricity demand - CZ	EU Power System	Driver	Demand
Electricity demand - PL	EU Power System	Driver	Demand
Electricity demand - AT	EU Power System	Driver	Demand
Electricity demand - CH	EU Power System	Driver	Demand
Electricity demand - FR	EU Power System	Driver	Demand
Electricity demand - SE	EU Power System	Driver	Demand
Electricity demand - IE	EU Power System	Driver	Demand
Electricity demand - BE	EU Power System	Driver	Demand
Electricity demand - DE	EU Power System	Driver	Demand
Electricity demand - DK	EU Power System	Driver	Demand
Electricity demand - NO	EU Power System	Driver	Demand
Electricity demand - GB	EU Power System	Driver	Demand

(*continued on next page*)

Table 17 (*continued*)

Activity	Sector	Type	List of technologies
Electricity BN	EU Power System	Energy	Electricity from Coal old, Electricity from Coal, Electricity from CCGT old, Electricity from CCGT, Electricity from Gas CHP, Electricity from GT, Electricity from Oil, Electricity from Waste, Electricity from Other RES, Electricity from Biomass, Electricity from Nuclear, Electricity from Hydro, Electricity from Onshore Wind, Electricity from Offshore Wind, Electricity from Solar, Pumped Hydro - Storage DE Undispatched Electricity (VOLL), Interconnection between countries
Electricity BU	EU Power System	Energy	
Electricity BT	EU Power System	Energy	
Electricity FI	EU Power System	Energy	
Electricity IT	EU Power System	Energy	
Electricity PT	EU Power System	Energy	
Electricity ES	EU Power System	Energy	
Electricity SK	EU Power System	Energy	
Electricity CZ	EU Power System	Energy	
Electricity PL	EU Power System	Energy	
Electricity AT	EU Power System	Energy	
Electricity CH	EU Power System	Energy	
Electricity FR	EU Power System	Energy	
Electricity SE	EU Power System	Energy	
Electricity IE	EU Power System	Energy	
Electricity BE	EU Power System	Energy	
Electricity DE	EU Power System	Energy	
Electricity DK	EU Power System	Energy	
Electricity NO	EU Power System	Energy	
Electricity GB	EU Power System	Energy	
Electricity NL - HVNS	NL Power System	Energy	Electricity from Offshore Wind
Electricity NL - HV	NL Power System	Energy	Electricity from Coal old, Electricity from Co-fired Coal, Electricity from Co-fired Coal wCCS, Electricity from CCGT, Electricity from CCGT wCCS, Electricity from GT, Electricity from Nuclear, Electricity from Biomass, Electricity from Onshore Wind, Electricity from Solar PV Fields, Electricity from Hydro, Undispatched Electricity (VOLL), Compressed Air Aboveground Storage, Compressed Air Underground Storage, Import from BE, Import from DE, Import from DK, Import from NO, Import from GB, Import from NS, Transformer from LV to HV, Transformer from MV to HV
Electricity NL - MV	NL Power System	Energy	Electricity from Industrial Solar PV, Transformer from HV to MV Baseload, Transformer from HV to MV Peaks, Transformer from LV to MV
Electricity NL - LV	NL Power System	Energy	Electricity from Residential Solar PV, Transformer from HV to LV, Transformer from MV to LV Baseload, Transformer from MV to LV Peaks

(*continued on next page*)

Table 17 (*continued*)

Activity	Sector	Type	List of technologies
Heat LT Network	District Heating	Energy	Boiler Gas, Boiler Gas wCCS, Boiler Biomass, Boiler Biomass wCCS, Geothermal Gas HP, Hot water storage tank
Road Fuel	Refineries	Energy	Deep cracking refinery; Deep cracking refinery wCCS; Basic cracking refinery; Basic cracking refinery wCCS; Koch refinery; Koch refinery wCCS; Bioethanol refinery from sugar; Bioethanol refinery from sugar wCCS; Bioethanol refinery from starch; Bioethanol refinery from starch wCCS; Bioethanol refinery from wood; Bioethanol refinery from wood wCCS; Biodiesel FAME refinery; Biodiesel FAME refinery wCCS; Biodiesel FT refinery from wood; Biodiesel FT refinery from wood wCCS; P2L methanol pathway, ext. H2, DAC; P2L methanol pathway, ext. H2, ext CO2; P2L FT pathway, ext. H2, DAC; P2L FT pathway, ext. H2, ext CO2; P2L methanol pathway, alk. electrolysis, DAC; P2L methanol pathway, alk. electrolysis, ext CO2; P2L FT pathway, alk. electrolysis, DAC; P2L FT pathway, alk. electrolysis, ext CO2
Hydrogen	Hydrogen	Energy	Gas Reforming, Gas Reforming wCCS, Alkaline electrolyser, Small scale storage buffer, Large scale storage buffer
Final Natural Gas	Natural Gas	Energy	Gas Extraction, Gas Import, LNG Import, Gas from Manure Digestion, Gas from Manure-Starch Co-Digestion, Gas from Solid Biomass Gasification, Gas from Solid Biomass Gasification wCCS, SynGas from Hydrogen, Small scale storage buffer, Large scale storage buffer
Biomass	Biomass	Energy	From primary to final Biomass
Coal	NL Primary Energy	Energy	Primary form
Crude Oil	NL Primary Energy	Energy	Primary form
Imported Natural Gas	NL Primary Energy	Energy	Primary form
National Natural Gas	NL Primary Energy	Energy	Primary form
Imported LNG	NL Primary Energy	Energy	Primary form
Uranium	NL Primary Energy	Energy	Primary form
Waste	NL Primary Energy	Energy	Primary form
Wet organic matter	NL Primary Energy	Energy	Primary form
Manure	NL Primary Energy	Energy	Primary form
Dry organic matter	NL Primary Energy	Energy	Primary form
Grass crops	NL Primary Energy	Energy	Primary form
Wood	NL Primary Energy	Energy	Primary form
Sugars	NL Primary Energy	Energy	Primary form
Starch	NL Primary Energy	Energy	Primary form
Vegetable Oil	NL Primary Energy	Energy	Primary form

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Table 17 (*continued*)

Activity	Sector	Type	List of technologies
Wind Energy	NL Primary Energy	Energy	Primary form
Solar Energy	NL Primary Energy	Energy	Primary form
Ambient Energy	NL Primary Energy	Energy	Primary form
Geothermal Energy	NL Primary Energy	Energy	Primary form
Solar Heat	NL Primary Energy	Energy	Primary form
Jet Kerosene	NL Primary Energy	Energy	Primary form
Heavy Oil for Shipping	NL Primary Energy	Energy	Primary form
Residual Heavy Oil Products	NL Primary Energy	Energy	Primary form
Residual Light Oil Products	NL Primary Energy	Energy	Primary form
Natural Gas Liquids	NL Primary Energy	Energy	Primary form
Coal EU	EU Primary Energy	Energy	Primary form
Oil EU	EU Primary Energy	Energy	Primary form
Gas EU	EU Primary Energy	Energy	Primary form
Nuclear EU	EU Primary Energy	Energy	Primary form
Waste EU	EU Primary Energy	Energy	Primary form
Biomass EU	EU Primary Energy	Energy	Primary form
Heat EU	EU Primary Energy	Energy	Secondary production of EU CHPs
nER-GHG CO2	Emissions	Emission	MACC Components
nER-GHG CH4	Emissions	Emission	
nER-GHG N2O	Emissions	Emission	
nER-GHG F-gas	Emissions	Emission	
CO2 CCUS Network	Emissions	Emission	CO2 Storage, CO2 from Direct Air Capture under ETS scheme, CO2 from Direct Air Capture outside ETS scheme, Small scale storage buffer
CO2 Air ETS	Emissions	Emission	ETS Allowance
CO2 Air n-ETS	Emissions	Emission	CO2 Emission
CO2 Air ETS EU	Emissions	Emission	ETS Allowance
CO2 Air Int. Transport	Emissions	Emission	CO2 Emission

in TIMES[40]). Thus, under a richly described technological landscape, there are many technology use combinations able to satisfy a desired volume of activities. From such a broad domain, the model simultaneously determines the optimal configuration and use of technologies to satisfy the required activities' volumes. It does so by minimizing system costs resulting from the set of decision variables confirmed by use, investments, decommissioning, and retrofitting of technologies accordingly with the following expression.

$$\min\left[\sum_{t,p} u_{t,p}VC_{t,p} + i_{t,p}\alpha_t IC_{t,p} + d^{pre}{}_{t,p}DF_t\alpha_t IC_{t,p} + r_{t_i,t_j,p}\alpha_{t_j}RC_{t_i,t_j,p} + s_{t,p}FC_{t,p}\right] \tag{1}$$

Subject to ensure that the use of technologies meets at least the required exogenous activities drivers, as described by

$$\sum_t u_{t,p}AP_{t,a,p} \geq V_{a,p} \tag{2}$$

Also subject, as shown in (3), to the available installed capacities of the technologies and the particular activity-to-capacity ratio for each technology, Γ_t.

$$u_{t,p} \leq s_{t,p}\Gamma_t \tag{3}$$

Every single technology can affect one of the five accounts of emissions considered as activities: CCUS network, national ETS, national non-ETS, external ETS, and international transport emissions. Most technologies increase the net volume of the emitting activity and some technologies decrease it (such as carbon capture and direct air capture). To keep the emission activities balanced there are four 'technologies' who match their net account, which are named: CO_2 released to air in the national ETS, national non-ETS, external ETS and international transport accounts. The emission constraint is therefore enforced by ensuring that the CO_2 released to air in the national ETS and non-ETS accounts does not exceed the national targets defined for the different periods as described by the following constraint:

$$\sum_{te} u_{te,p} \leq E_p \tag{4}$$

Nevertheless, it is important to mention that not all the sources of emissions considered within the scope of the targets are included within the activities that are covered by IESA-Opt. To be precise roughly 85% of the emissions considered within the 2017 national inventory [47] are covered by the activities included in the energy system framework, then for the remaining 15% (mostly agricultural activities), a less detailed approach is used. Here, the emissions resulting from activities such as enteric fermentation, manure management, use of fertilizers and use of refrigeration fluids are input to the model as driving activities, and their potential reductions and costs are addressed with MACC curves (extracted from the IMAGE model database [41]). A complete description of the methodology is provided in Appendix D.

Next to the previous formulation, other aspects must be included to better represent the feasible operation of the energy system. These aspects are an adequate multi-year transitional path representation, the hourly representation of the European power system despatch, including the flexibility representation and technical limits in the operation of flexible demand and generation technologies, the consideration of gaseous networks operation and the impact of available infrastructure in the intra-year operation of technologies.

C.2. Transition path

The transitional capability of the model derives from the fact that it can plan for the optimal system configuration for the different periods covered in the transition, at the same time that it determines the optimal intra-year operation of the stocks. The transitional elements are described by the investment, premature decommissioning, and retrofitting decisions that give shape to the technological stock accordingly with the following formulation:

$$s_{t,p} = s_{t,p-1} + i_{t,p} + r_{t^i,t,p} - r_{t,t^i,p} + ({d^{cum}}_{t,p} - {d^{cum}}_{t,p-1}) \tag{5}$$

being:

$${d^{cum}}_{t,p} = {d^{cum}}_{t,p-1} + {d^{pre}}_{t,p} + {d^{lt}}_{t,p} \tag{6}$$

It is important to ensure that premature decommissioning can freely happen at any period if convenient, but to avoid that decommissioned technologies cannot be decommissioned in a year and recommissioned back in a subsequent period. Simultaneously, the model must be able to address the costs of premature decommissioning. For this purpose, the following constraint together with (5) and (6) ensure both requirements to be satisfied:

$${d^{cum}}_{t,p} \geq {d^{cum}}_{t,p-1} \tag{7}$$

Also, as part of the scenario descriptions, some technologies are defined within a certain bandwidth of deployment. This same constraint, depicted in (8), is used to set the adoption potentials for technologies and to cap system emissions.

$${S^{min}}_{t,p} \leq s_{t,p} \leq {S^{max}}_{t,p} \tag{8}$$

Lastly, the retrofitting of technologies is constrained by the available stocks of the original technology, and by an input binary parameter which determines which are the possible retrofitting relations. This results in the following formulation:

$$r_{t_i,t_j,p} \leq s_{t,p-1} RM_{t_i,t_j} \tag{9}$$

C.3. European hourly power sector despatch

Modelling power despatch within ESMs asks for choices to be made to avoid enormous computational requirements. To start with, the study [23] concluded that considering poor temporal resolutions negatively affects outcomes reliability for scenarios with moderate and high presence of VRES, and greatly recommend to prioritize using at least hourly resolution. Also, adopting a sequential description of the power despatch enables to retain the chronological order in the variability of the events, which is key for short and long term storage technologies. Thus, IESA-Opt adopted an hourly resolution of the complete year operation (8760 sequential points per year).

Furthermore, the same study [23] also mentions that operational detailing, namely unit commitment, increases reliability as the presence of VRES start to increase. However, it also states that adopting unit commitment loses relevance after a certain level of VRES penetration, as fewer thermal units affect the system dynamics. This observation is further reinforced by another study which states that MIP unit commitment performs better in scenarios with low presence of VRES, but for scenarios with high levels of VRES an LP approach suffices to provide reliable results [24]. Also, there is plenty of evidence that increasing the geographical scope of the model to consider European cross-border interactions has a significant impact on the outcome reliability of the models [58,59]. Therefore, in this model we exclude the unit commitment formulation (MIP) and rather include the whole European power system represented in 20 nodes (see Appendix C). This penalizes the ability of the model to reliably analyse low VRES scenarios with a high presence of thermal generators (as unit commitment is excluded), but keeping the convenient LP formulation enables IESA-Opt to simultaneously solve the EU power despatch and the integrated national energy system within the same formulation while considering a high temporal resolution and a moderate and high presence of VRES. Thanks to such modelling choice it is possible to analyse the interaction of storage, flexible demand technologies, VRES, and cross-border interconnection within the sector-coupled energy system of the Netherlands.

The following linear formulation is used to include the previously described concepts within the IESA-Opt framework. First, the fundamental constraint that supply and demand of electricity must remain balanced at every hour is included. For this purpose, we divide technologies into five main groups: dispatching technologies, t_d, technologies with flexible, t_{pf}, and non-flexible operation, t_{pn}, flexible CHPs, t_c, and shedders, t_s. For each of the 24 different electricity networks considered in the model, conforming the set A^e, the hourly balance is represented with the following constraint:

$$\begin{aligned} u_{h,td,p} AP_{td,a,p} = {} & u_{t_p,p} P_{h,tp} AP_{tp,a,p} + \left(\Delta {q^{up}}_{h,tf,p} + \Delta {q^{dw}}_{h,tf,p}\right) AE_{tf,a} \\ & + \left(u_{tc,p} P_{h,tc} + \Delta u_{h,tc,p}\right) AP_{tc,a,p} + \Delta p_{h,tc,p} AE_{tc,a} \\ & + \left(u_{ts,p} P_{h,ts} + \Delta u_{h,ts,p}\right) AP_{ts,a,p} \quad \forall\ a | a \in A^e \end{aligned} \tag{10}$$

This equation can be read as supply is equal to reference hourly demand, plus flexible demand variations ($\Delta {q^{up}}_{h,tf,p}$ and $\Delta {q^{dw}}_{h,tf,p}$), plus the bi-dimensional CHP flexibility variations ($\Delta u_{h,tc,p}$ and $\Delta p_{h,t_c,p}$), and plus the shedding demand variations ($\Delta u_{h,ts,p}$), for each interconnected node. These three forms of flexibility are further explained in Section 3.4.

Another major determinant for the despatch of electricity is resource availability, and this turns relevant for two reasons: the installed capacities of generation technologies and the intermittency of renewable energy sources. Every single technology in the model is described with an hourly operation $P_{h,t}$. For the dispatching technologies, this profile represents the hourly availability of the resource, and for the other technologies, it represents the hourly reference operation.[22] The following constraint ensures that supply occurs accordingly with the existent installed capacity and to the extent at which the hourly resource availability allows it:

$$u_{h,td,p} \leq s_{td,p} \Gamma_{td} P_{h,td} \tag{11}$$

Also, ramping constraints are considered for dispatchable generation accordingly with the following constraint:

$$-R^{dw}_{td,p} \leq \left(u_{h,td,p} - u_{h-1,td,p}\right) \leq R^{up}_{td,p} \tag{12}$$

Lastly, the European representation, the despatch architecture, the data on profiles and operational parameters are strongly based on the same modelling structure used as input by COMPETES model [13]. Further details can be found in Appendix C.

C.4. Hourly flexible operation in coupled sectors

Next to the power despatch description, the representation of possible deviations from reference hourly operation profiles are paramount

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[22] The profiles are normalized and extracted from historical datasets such as the wind and solar availability in the Netherlands and the other 20 considered EU regions; the load profile of the Netherlands and EU regions; reference EV charging and connection profiles; temperature profiles; and a flat profile. Due to availability of data, so far only 84 hourly profiles have been included, but every technology is assigned to one of them, which means that many technologies share profiles. However, if more data becomes available the model is already enhanced to easily include it into the database, and would not result in increased computational times.

for the despatch and to adequately represent sector coupling. With this aim, IESA-Opt considers three different types of intra-year operational decisions: flexible CHPs, shedding technologies, and demand technologies with flexible operation.

C.4.1. Flexible CHP's. CHPs are modelled as operation technologies, which means that their hourly operation profile is fixed, and the changes in their use affect such profiles proportionally. However, some CHPs, known as extraction-condensing steam turbines, can extract a fraction of the condensed steam before (or during) the expansion phase (the power turbine) to be used to provide heat [60,61]. Such enhancement allows these turbines to adjust their power-to-heat ratio, which in combination with the amount of steam generated before the expansion, gives the technology a huge potential to modify its power and heat outputs and fuel inputs to adapt to electricity price events (amongst other externalities) [62]. The resulting bi-dimensional flexibility (the fuel inputted into the boiler, and the extraction flow of the condensed steam) is considered by IESA-Opt using a convenient LP simplification (resembling other ESMs [63]).

In a linear representation of a flexible CHP, the fuel requirement, F, is assumed to be determined by the heat and power outputs, H and P, accordingly with $F = {}^{H}/_{\eta} + {}^{P}/_{\varepsilon}$. Where η and ε represent the CHPs' efficiencies when producing only heat and power respectively. For this, IESA-Opt considers two dimensions in which flexibility takes place: the hourly deviations in the fuel input representing the deviations in use, $\Delta u_{h,t_c,p}$; and the hourly deviations in the power output, $\Delta p_{h,t_c,p}$. This leads to the following constraint to ensure satisfying heat the heat demand provided by the CHP, in a specific time window:

$$\sum_{h \in TW_{tc}} \left[\left(u_{tc,p} P_{h,tc} + \Delta u_{h,tc,p} \right) AP_{tc,a,p} - {}^{\eta_{tc}}/_{\varepsilon_{tc}} \Delta p_{h,tc,p} \right] = \sum_{h \in TW_{tc}} u_{tc,p} P_{h,tc} AP_{tc,a,p} \tag{13}$$

As the model distinguish from different temperature levels and different sectors, A^h represents the set of activities corresponding to the different heat forms that can be produced by the different CHPs in the model.

C.4.2. Shedding technologies. The upcoming energy transition will deliver a set of technologies that could provide sector coupling via the conversion of electricity into other energy forms (such as heat [29], hydrogen [30], methanol [31], methane [32], hydrocarbons [64], chlorine [34], ammonia[35], and other chemicals [28]) via the means of technologies such as heat pumps or electrolyzers. We use the word shedding to refer to the action taken by abovementioned technologies of cutting down operations in a critical hour to decrease electricity consumption and help to alleviate the system. This opens the door to foreseeable scenarios where these type of technologies could be interruptedly operated to avoid high electricity price events and decrease their operational costs [28]. However, extra capacity must be installed to be able to satisfy demand while sacrificing operational times [27]. Summarizing, shedding technologies in IESA-Opt can selectively operate in specific hours in exchange for overinvestments.

The representation of these technologies in the model assumes they can shed their hourly activities by the means of an hourly decision variable which represents the decrease in use for each hour. This variable is capped by the installed capacity of the technology, as shown below:

$$\Delta u_{h,ts,p} \le s_{ts,p} SC_{ts} UtP_{ts,p} \tag{14}$$

Because, as stated in (2), the model must ensure sufficiency in the activities balances, it will determine the required technological stock, determining in this way the necessary excess capacity to cope with such shedding.

Furthermore, technologies might not have a flat operational profile and might be subject to specific sectoral dynamics, or perhaps a certain technology may require a minimum level of operation. For these cases the following constraint is imposed:

$$\Delta u_{h,ts,p} \le u_{ts,p} P_{h,ts} SF_{ts} \tag{15}$$

where SF_{t_s} represents the assumed potential shedding fraction of each shedding technology. And the profile is flat for technologies without specific sectoral dynamics.

C.4.3. Conservative flexibility. The last element presented here consists of the formulation used for technologies that allow for deviations in the reference profile without compromising the technology output and with or without paying an efficiency penalty. We call these options here as conservative flexibility, as all the up or down flexibility must be eventually recovered with an action in the opposite direction. Some examples of these technologies are some residential and services appliances such as dishwashers, washing machines, fridges or freezers [5,36]; electric heating appliances with active or passive storage [38,65,66]; electric vehicles with smart charging or vehicle-to-grid enhancements [39]; industrial processes with opportunities for flexible programming of their operations [5,67–69]; and all sort of different kind of batteries and storage technologies [26,70,71,71].

To be able to model such a vast group of technologies, they were grouped into 4 different archetypes[23]: load shifting for typical demand response and active thermal storage; smart charging of electric vehicles; vehicle-to-grid; and storage technologies. Each of these groups is represented under a specific formulation in the model and can be applied to all of the technologies considered under each category. However, all of the formulations share three elements in common: a balance constraint, a capacity constraint, and a saturation constraint, and each of the elements is interpreted differently for each archetype.

The energy balance states that the net energy demand should remain constant for the considered time window, and the use of time windows is adopted to maintain a linear formulation of the balance. This implies that the net balance of the upwards and downwards gross shifted load within the time window should be equal to the corresponding losses if any, as follows:

$$\sum_{h \in TW_{tf}} \Delta q^{up}{}_{h,tf,p} + \sum_{h \in TW_{tf}} \Delta q^{dw}{}_{h,tf,p} = \sum_{h \in TW_{tf}} l_{h,tf,p} \tag{16}$$

Both upward and downward shifts are subject to a physical capacity constraint determining the minimum and maximum boundaries of the feasible rescheduling capacity. For instance, this constraint in flexible heat-pumps sets the maximum available upward shift equal to the difference between reference profile and heat-pump's maximum capacity. These limits can be asymmetrical to each other and can be hourly variables. This second element is illustrated in the two following equations:

$$\Delta q^{up}{}_{h,tfp} \le \Delta q^{max}{}_{h,tf,p} \tag{17}$$

$$\Delta q^{dw}{}_{h,tf,p} \ge \Delta q^{min}{}_{h,tf,p} \tag{18}$$

Finally, a saturation constraint ensures that the shifted volume does not violate a feasible operational limit, such as the storage capacity of an active storage unit or a latent heat requirement of a built environment system. These saturation limits can be either fix or represented by a combination of parameters and variables depending on the archetype involved, therefore the third type of constraints follow the below structure:

$$v^{min}{}_{h,tf,p} \le \sum_{h \in TW_{tf}} \left[B^{up} \Delta q^{up}{}_{h,tf,p} + B^{dw} \Delta q^{dw}{}_{h,tf,p} \right] \le v^{max}{}_{h,tf,p} \tag{19}$$

B^{up} and B^{dw} are two conceptual binary parameters used to illustrate that the saturation constraint can be imposed independently on both shift directions.

The interpretation of these three forms of constraints is presented below for all the 4 presented archetypes.

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[23] There is a fifth archetype considered by the model: load recovery for passive or latent thermal storage [39,87]. However, as it plays no role in the results obtained in this scenario, it was excluded from this description.

Demand Response

This form of flexibility assumes that the application of flexibility is capped by the installed capacity of the technology. This directly affects the capacity constraint interpretation stating that the maximum upward deviation available is given by the difference between the installed capacity and the use of the technology determined by the hourly profile in the following way:

$$\Delta q^{up}{}_{h,tf,p} \leq \left(s_{tf,p}FC_{tf} - u_{tf,p}P_{h,tf}\right)AE_{tf,a} \tag{20}$$

and the maximum upward deviation is given by the ability of the technology to decrease it's reference hourly consumption given by

$$\Delta q^{dw}{}_{h,tf,p} \leq \left(1 - NN_{tf}\right)u_{tf,p}P_{h,tf}AE_{tf,a} \tag{21}$$

The volume constraint ensures that the reallocated energy consumption within a time window does not exceed the original total consumption of the time window, nor upwards nor downwards as shown below.

$$\sum_{h\,\in\,TW_{tf}} \Delta q_{h,tf,p} \leq \sum_{h\,\in\,TW_{tf}} u_{tf,p}P_{h,tf}AE_{tf,a} \tag{22}$$

Storage

The interpretation of the capacity constraint for storage is given by the (dis)charging capacity. The maximum amount of flexibility that any storage technology can provide is determined by the following constraint:

$$\Delta q_{h,tf,p} \leq s_{tf,p}CC_{tf} \tag{23}$$

The interpretation of the volume constraint for storage is marked by the storage capacity as described by the theoretical charging time of a battery accordingly with the following constraint.

$$\sum_{i\leq h} \Delta q_{i,tf,p} \ \leq s_{tf,p}CC_{tf}CT_{tf} \tag{24}$$

Smart Charging and Vehicle-to-Grid

The main characteristic of these forms of flexibility is that they are dependant on the number of vehicles connected to the grid in a given moment. Thus, the upward capacity is capped by the difference between the charging capacity of connected EV's and the reference charging profile as given by:

$$\Delta q^{up}{}_{h,tf,p} \leq CC_{tf}\left(s_{tf,p} - \frac{u_{tf,p}VU_{h,tf}}{AS_{tf}}\right) - u_{tf,p}P_{h,tf}AE_{tf,a} \tag{25}$$

While the downwards flexibility is constrained by the reference consumption and the non-negotiable load for smart charging:

$$\Delta q^{dw}{}_{h,tf,p} \leq \left(1 - NN_{tf}\right)u_{tf,p}P_{h,tf}AE_{tf,a} \tag{26}$$

And by the discharging capacity of connected vehicles for vehicle-to-grid flexibility:

$$\Delta q^{dw}{}_{h,tf,p} \leq DC_{tf}\left(s_{tf,p} - \frac{u_{tf,p}VU_{h,tf}}{AS_{tf}}\right) \tag{27}$$

The volume constraint for both Smart Charging and V-to-G is given similar to the storage, where the cumulative application of flexibility cannot exceed the difference between the available storage capacity of connected vehicles and the minimum required stored energy for the journeys of the vehicles departing in that hour given by:

$$\sum_{i\leq h} \Delta q_{i,tf,p} \leq CC_{tf}CT_{tf}\left(s_{tf,p} - \frac{u_{tf,p}VU_{h,tf}}{AS_{tf}}\right) - \sum_{h\leq i\leq h+AJ} u_{tf,p}P_{i,tf}AE_{tf,a} \tag{28}$$

C.5. Operation of gaseous networks

Integrated electricity and gas models usually focus on designing a proper nodal representation of the network based on pressure tolerances and Bernoulli equations, intending to provide detailed planning and operation optimization [72]. Because of the large scope of the problem and specific goals of the methodology, IEM often ignores any type of detailed description of the gas system. However, because we aim to address seasonality, buffer opportunities, and infrastructure costs, IESA-Opt includes a simplified representation of gaseous networks operation based on a daily balance despatch approach [17]. This representation is presented below.

Gas networks, as transporters of a compressible fluid, are inherently provided with a buffer which allows for damping (i.e. the temporal discoordination between the input and output flows to the gas network) [17]. However, operation of the network must occur within safety pressure boundaries, meaning that the size of the buffer has limits (and regions), thus requiring intra-day balancing actions to keep networks functional.[24] There is no specific balancing period in this scheme. The imbalances are corrected when the magnitude of the imbalance reaches a certain predefined level [18].

A daily balancing approach was selected for activities distributed by the network of gaseous pipelines. This approach was selected first due to the previously described damping characteristic, and second, due to a typical daily flat price profile resulting from models with the hourly balancing of gas despatch [73]. Such modelling choice allows for dispatching national wells and imports, considering the daily operation of the buffers (e.g., gas storage chambers), and describing other generation processes with particular sectoral dynamics such as fermentation, (bio)gasification, and methanation.[25] However, this representation cannot provide network planning or operation of circulating compressors. Finally, the same approach is used for all the gases transported in pipelines, namely, natural gas (HD, MD, and LD), hydrogen (HD and LD), and sequestered carbon dioxide for CCUS.

Similar to the electric balancing description, the gas despatch is described for each day accordingly with:

$$u_{d,td,p}AP_{td,a,p} = u_{tp,p}P_{d,tp}AP_{tp,a,p} + \left(\Delta q^{up}{}_{d,tg,p} + \Delta q^{dw}{}_{d,tg,p}\right)AG_{tg,a} \tag{29}$$

Also, the daily despatch technologies, analogously to the power despatch, are bounded by their daily availability profiles and installed capacities accordingly with:

$$u_{d,td,p} \leq s_{td,p}\Gamma_{td}P_{d,td} \tag{30}$$

C.6. Infrastructure description

The infrastructure imposes a limitation to the system in terms of the extent an activity can be carried out within a certain time-frame and geographical area. This restriction provides an extra incentive for flexibility as it can avoid network reinforcement costs [72]. Furthermore, infrastructure descriptions help to provide a better representation of the expected transitional costs, as the energy system must adapt to enable the deployment of infrastructure intensive technologies, such as CCUS, hydrogen, and district heating. The infrastructure representation adopted in IESA-Opt is presented in Table 18.

The activities constrained by available infrastructure are described with daily and hourly timeframes. For the hourly ones, infrastructure limits the volumes of the activity in a time frame accordingly with:

$$\begin{aligned}&\left(u_{t,p}P_{h,t} + \Delta u_{h,ts,p}\right)AP_{t,a,p} + \left(\Delta q^{up}{}_{h,tf,p} + \Delta q^{dw}{}_{h,tf\ |\ tf\neq tf_b,p}\right)AE_{tf,a}\\ &\leq s_{ti_h,p}\Gamma_{ti_h}\forall\ a\ |a\ \in\ A^e\ \&\ \forall\ t\ |AP_{t,a,p} > 0\end{aligned} \tag{31}$$

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[24] There are different types of balancing actions designed accordingly with the size of the imbalance. As reference of the magnitude, no balancing action is required for hourly imbalances of ~2% of the daily market volume. In average, 3 balancing actions per day were required between November 5th 2019 and December 4th 2019 [17] (high demand season).

[25] Methanation, as an electricity consumer, is already subject to hourly shedding constraints (section 2.4). Thus, the daily gas dispatch formulation further restricts its operation.

Table 18
Considered infrastructure technologies in IESA-Opt.

Technology	Activity	Time frame
Final natural gas HD grid pipeline	HD Final natural gas	1 day
Final natural gas MD grid pipeline	MD Final natural gas	1 day
Final natural gas LD grid pipeline	LD Final natural gas	1 day
Hydrogen HD grid pipeline	HD Hydrogen	1 day
Hydrogen LD grid pipeline	LD Hydrogen	1 day
CCUS grid pipeline	CCUS	1 day
HV Electricity grid cable	HV Electricity	1 h
MV Electricity grid cable	MV Electricity	1 h
LV Electricity grid cable	LV Electricity	1 h
LT Heat distribution network pipeline	LT Heat distribution network	1 h

Very similarly, the model considers the following constraint for the daily described infrastructure technologies, t_{id}:

$$\left(u_{tp,p}P_{d,tp} + \Delta u_{h,tc,p} + \Delta u_{h,ts,p}\right)AP_{tp,a,p} + \left(\Delta q^{up}{}_{d,tf,p}\right)AG_{tf,a} \le s_{ti_d,p}\Gamma_{ti_d}$$
$$\forall\ a \mid a \in A^g \& \ \forall\ t \mid AP_{t,a,p} > 0 \qquad (32)$$

Other elements of the energy infrastructure, such as transformers and buffers, are considered as operational technologies. Thus, both their investment and operational costs are determined as for any other operational technology within the model. Therefore, the formulation presented in this section only refers to infrastructure which exerts no action other than enabling the flow of an activity to a certain volume.

Appendix D. Consideration of non-energy related emissions in IESA-Opt

To cover all the GHG emissions forms considered within the decarbonization reduction targets, data from the national GHG emission inventory report 2017 was used [47]. This helped to identify which emissions were not yet covered by the model, and to prioritize which emission sources should be included to increase robustness in the emission reduction analysis. The summary of the sources, emission activity, emission form, evolution from 1990 to 2017, and how the model deal with each is presented in Table 19.

Based on the inventory shown in the above table, the following approach was used to include the emission sources into IESA-Opt. First, from all the emissions that were not yet explicitly accounted by the activities in IESA-Opt as fuels or industrial processes (which account for 85% of the total emissions in 2017), the most significant ones were extracted. Being the latter: enteric fermentation (CH4), manure management (CH_4 and N_2O), organic and inorganic fertilizers (N_2O), and refrigeration (HFC). Another reason for the selection of these sources is that reliable data was found to incorporate their MACC curves into the model accordingly with IMAGE model database [41,74].

Based on above data, the following activities were defined to include all non-energy related emissions into IESA-Opt:

1 CH_4 emissions from enteric fermentation.
2 CH_4 emissions from manure management.
3 CH_4 emissions from other sources (aggregated).
4 N_2O emissions from manure management.
5 N_2O emissions from fertilizer utilization.
6 N_2O emissions from other sources (aggregated).
7 F-gas emissions from use of HFC as refrigeration fluid.
8 F-gas emissions from other sources (aggregated).
9 CO_2 emissions from other sources (aggregated).

The resulting MACC curves used in IESA-Opt for the nine above mentioned sources of non-energy related GHG emissions are reported on Fig. 27.

Appendix E. EU Power system representation in IESA-Opt

The representation of the EU power system is mainly extracted from COMPETES model [13] in terms of nodal representation and technologies considered, as well as the parameters used for IESA-Opt. In terms of the nodal representation, only one modification was made to COMPETE's representation, and this was to join both eastern and western Denmark nodes into one single node.

The operational parameters of the generation technologies required by the model consist of both economical and operational components. The list of technologies, and operational parameters assumed for the European power system are shown in the following table.[27]

Technology	Investment 2020	Investment 2050	FOM	VOM	LT	Ramp	Eff.
Units	[M€/GW]	[M€/GW]	[M€/ GW-y]	[M€/ GWh]	[y]	[%]	[GWhf/ Gwhe]
Coal old	1823.8	1809.4	18.3	2.6	40	0.5	2.41
Coal	1823.8	1809.4	18.3	2.3	40	0.5	1.79
CCGT old	899.2	892.1	11.3	1.8	30	0.8	2.49
CCGT	899.2	892.1	11.3	1.6	30	0.9	1.69
Gas CHP	1016.0	1008.0	12.7	1.6	20	0.9	2.89
GT	562.0	557.5	7.0	1.0	20	1	2.81
Oil	613.5	613.5	7.8	2.6	20	1	3.01
Waste	2254.4	2254.4	112.7	2.6	20	1	3.13
Other RES	3576.9	3191.1	0.0	3.8	20	1	1
Biomass	2657.4	2229.1	42.3	2.6	20	1	2.44
Nuclear	5636.0	5636.0	70.5	6.4	60	0.2	3.12
Hydro	4284.0	4205.1	10.8	1.1	45	1	1
Onshore Wind	1259.7	1074.5	17.2	1.6	20	1	1
Offshore Wind	1830.8	1102.0	186.0	2.1	20	1	1
Solar	764.9	279.1	2.0	0.4	20	1	1
Pumped Hydro	1252.4	1252.4	4.8	0.0	20	1	1.43
Undispatched	NA	NA	NA	3000	NA	1	NA
Interconnection	(220-650)	(220-650)	(5.5-16.25)	0	50	1	1.02

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[27] Not all the countries have all the technologies present. The specific country composition of technologies is extracted from [13] and can be found in Appendix D.

Table 19
Summary of the inventory of emission sources and forms in the Netherland excl. LULUCF.

Source	Activity detailed	Form	Units	1990	2016	2017	Modelled
Energy related	Fuel Combustion	CO2	MtonCO2eq	154.5	158.6	156.2	Explicitely
Agriculture	Enteric fermentation	CH4	MtonCO2eq	9.2	8.8	8.7	MACC
Agriculture	Manure management	CH4	MtonCO2eq	5.4	3.9	3.9	MACC
Industrial Production	Ammonia production	CO2	MtonCO2eq	3.7	3.8	3.9	Explicitely
Waste	Managed waste disposal on land	CH4	MtonCO2eq	13.7	2.8	2.6	Aggregated
Energy related	Fuel Combustion	CH4	MtonCO2eq	0.9	1.6	1.7	Explicitely
Agriculture	Inorganic fertilizers	N2O	MtonCO2eq	2.5	1.5	1.6	MACC
Industrial Production	Refrigeration	HFC	MtonCO2eq	0	1.5	1.5	MACC
Agriculture	Organic N fertilizers	N2O	MtonCO2eq	0.8	1.3	1.4	MACC
Energy related	Fugitive Emissions	CO2	MtonCO2eq	0.9	1.1	1.1	Excluded
Agriculture	Urine and dung from grazing animals	N2O	MtonCO2eq	3	0.9	0.9	Aggregated
Agriculture	Manure management	N2O	MtonCO2eq	0.9	0.8	0.8	MACC
Industrial Production	Caprolactam production	N2O	MtonCO2eq	0.7	0.8	0.8	Explicitely
Industrial Production	Other mineral use	CO2	MtonCO2eq	0.48	0.77	0.79	Aggregated
Agriculture	Cultivation of organic soils	N2O	MtonCO2eq	0.9	0.7	0.7	Aggregated
Industrial Production	Other chemical industry	CO2	MtonCO2eq	0.6	0.5	0.7	Explicitely
Agriculture	Indirect N2O Emissions from managed soils	N2O	MtonCO2eq	1.6	0.6	0.6	Aggregated
Energy related	Fuel Combustion	N2O	MtonCO2eq	0.3	0.6	0.6	Explicitely
Energy related	Fugitive Emissions	CH4	MtonCO2eq	1.9	0.6	0.5	Excluded
Industrial Production	Petrochemical and carbon black production	CO2	MtonCO2eq	0.3	0.5	0.5	Explicitely
Industrial Production	Indirect CO2 emissions	CO2	MtonCO2eq	0.9	0.5	0.5	Aggregated
Agriculture	Crop residues	N2O	MtonCO2eq	0.5	0.3	0.3	Aggregated
Industrial Production	Cement production	CO2	MtonCO2eq	0.42	0.24	0.3	Aggregated
Industrial Production	Nitric Acid production	N2O	MtonCO2eq	6.1	0.3	0.3	Aggregated
Industrial Production	Petrochemical and carbon black production	CH4	MtonCO2eq	0.3	0.3	0.3	Explicitely
Industrial Production	Lime production	CO2	MtonCO2eq	0.16	0.17	0.23	Aggregated
Industrial Production	Paraffin wax use	CO2	MtonCO2eq	0.1	0.2	0.2	Aggregated
Industrial Production	Other ODS Substitute	HFC	MtonCO2eq	0	0.2	0.2	Aggregated
Waste	Wastewater treatment and discharge	CH4	MtonCO2eq	0.3	0.2	0.2	Excluded
Industrial Production	Ceramics	CO2	MtonCO2eq	0.14	0.12	0.12	Aggregated
Industrial Production	Other Soda Ash uses	CO2	MtonCO2eq	0.07	0.12	0.12	Aggregated
Industrial Production	Fluorochemical production	HFC	MtonCO2eq	6.4	0.2	0.1	Aggregated
Industrial Production	Lubricant use	CO2	MtonCO2eq	0.1	0.1	0.1	Aggregated
Industrial Production	SF6 and PFC from other product use	SF6	MtonCO2eq	0.3	0.1	0.1	Aggregated
Industrial Production	N2O from product uses	N2O	MtonCO2eq	0.2	0.1	0.1	Aggregated
Waste	Biological treatment of solid waste	CH4	MtonCO2eq	0	0.1	0.1	Excluded
Waste	Biological treatment of solid waste	N2O	MtonCO2eq	0	0.1	0.1	Excluded
Waste	Wastewater treatment and discharge	N2O	MtonCO2eq	0.2	0.1	0.1	Excluded
Industrial Production	Glass production	CO2	MtonCO2eq	0.14	0.1	0.008	Aggregated
Agriculture	Liming	CO2	MtonCO2eq	0.2	0	0	Excluded
Industrial Production	Fluorochemical production	PFC	MtonCO2eq	0	0	0	Excluded
Industrial Production	Iron and steel production	CO2	MtonCO2eq	0.05	0	0	Excluded
Industrial Production	Aluminium production	CO2	MtonCO2eq	0.45	0.1	0	Excluded
Industrial Production	Aluminium production	PFC	MtonCO2eq	2.6	0	0	Excluded
Industrial Production	Other non-specified	CO2	MtonCO2eq	0	0	0	Excluded
Industrial Production	Semiconductors	PFC	MtonCO2eq	0	0.1	0	Excluded
Industrial Production	Other processs emissions	CO2	MtonCO2eq	0.1	0	0	Excluded
Total				222	195	193	

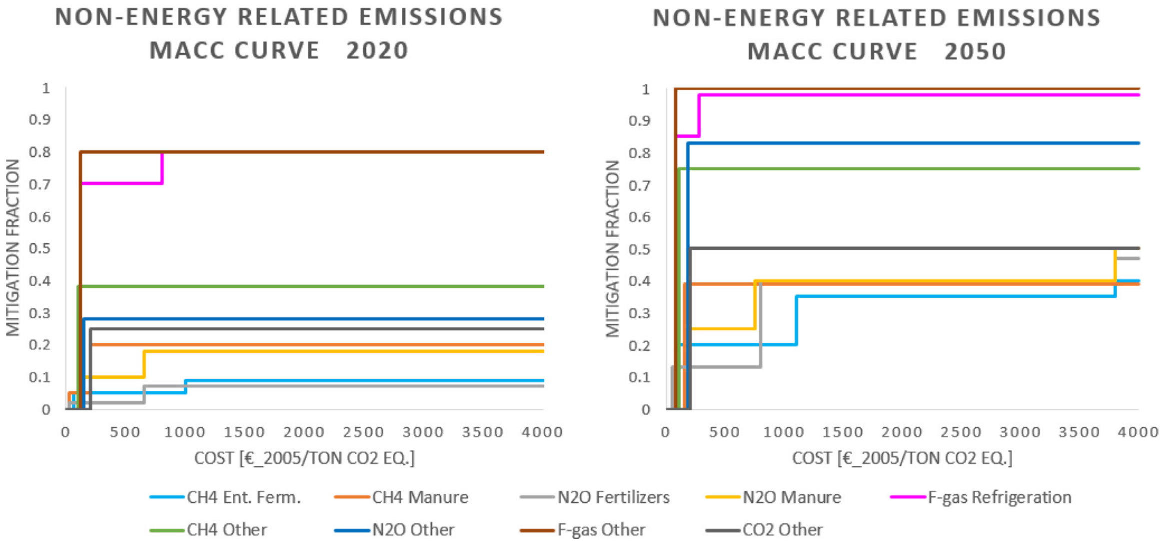

Fig. 27. MACC curves of non-energy related GHG emissions for years 2020 and 2050 as considered in IESA-Opt.[26]

Table 20
Activity volumes considered in the Reference Scenario.[28]

Sector	Driver	Units	Values				Source
			2020	2030	2040	2050	
General	Heat degree days	[HDD]	2900	2800	2700	2600	[76]
Residential	Appliances electricity demand	[PJ]	84.70	88.10	90.50	92.10	[77]
	Number of houses	[Mhouses]	8.2	8.8	9.2	9.6	[77,50]
Services	Appliances electricity demand	[PJ]	129.9	131.6	133.3	135.0	[77]
	Used space	[Mm^2]	515	540	555	560	[77]
Agriculture	Appliances electricity demand	[PJ]	36.8	38.0	42.5	47.0	[77]
	Heat demand for horticulture	[PJ]	87.2	92.0	96.8	101.5	[77,50]
	Heat demand for agriculture	[PJ]	8.4	8.8	9.2	9.6	[77,50]
	Machinery consumption	[PJ]	22.8	25.3	27.7	30.2	[77]
Industry	Steel production	[Mton]	7.0	6.7	6.8	7.3	[77]
	Aluminium production	[Mton]	0.2	0.2	0.2	0.2	[77,50]
	Ammonia production	[Mton]	2.8	3.0	3.2	3.4	[75]
	HV Chemicals production	[Mton]	7.2	7.7	8.3	8.7	[77,50]
	Other ETS Chem. Industry	[Index]	1.0	1.2	1.3	1.6	[77,50]
	Other ETS Industry	[Index]	1.0	1.0	1.1	1.1	[77,50]
	Other non-ETS Industry	[Index]	1.0	1.0	1.0	1.0	[77,50]
	Machinery consumption	[PJ]	43.0	45.2	47.0	49.5	[77]
Waste	Waste Incineration	[Mton]	7.6	9.1	10.6	12.3	[77,50]
	Waste Sewage	[PJ]	3.7	4.3	5.0	5.6	[50]
	Waste Landfill	[PJ]	0.4	0.1	0.0	0.0	[50]
Transport	Motorcycles	[Gvkm]	5.1	5.9	6.5	7.2	[77]
	Passenger Cars	[Gvkm]	110.5	114.3	119.2	125.3	[77]
	Light-Duty Vehicles	[Gvkm]	21.1	24.3	27.4	32.3	[77]
	Heavy-Duty Vehicles	[Gvkm]	7.4	7.7	8.0	8.3	[77]
	Buses	[Mvkm]	617.2	624.5	637.3	650.0	[77]
	Rail	[Mvkm]	170	200	215	230	[77]
	Intra-EU Aviation	[Mvkm]	210	260	340	430	[77]
	Extra-EU Aviation	[Mvkm]	670	740	790	850	[77]
	Inland-Domestic Navigation	[Mvkm]	55	70	80	90	[77]
	International Navigation	[Mvkm]	110	125	135	145	[77]
Emissions	Other CO_2 Emissions	[MtonCO$_2$]	26.6	24.0	21.7	19.6	[47,78,79]
Power EU	EU Electricity demand	[EJ]	11.7	11.8	12.0	11.9	[13]

Appendix F. Scenario description

F.1. Demand volumes

The model requires economic drivers to determine the optimal way in which energy must be supplied. For this purpose, the model considers national economic activities for the residential, services, agricultural, industrial and transport sectors, considering the activities shown in Appendix B for each of the sectors. Also, next to the national economic activities, the model requires the expected demand for electricity in European countries. The sources used to define the scenario presented in this paper (Table 20) are mainly based on the JRC's POTEnCIA Central Scenario storyline for the Netherlands [42]. JRC's data is complemented with databases from TNO's power despatch model COMPETES' scenario based on TYNDP Midterm Adequacy Forecasts 2016 and Sustainable Transition scenario [13,52]; data from PBL's ENSYSI model reference scenario [50]; and the 2019 Netherland's Climate Energy Outlook [75]. The scenario is based on existing policies and measures, and considers GDP growth rates in line with the 2018 Ageing Report [43].

F.2. Resources' costs

The model satisfies the need for energy demands by the combination of primary energy supply, conversion of primary energy in final energy and final energy imports. Therefore, the costs assumed for the primary assets supplied to the system are direct input to the model and key part of the scenario definition. It should be noted that the future price levels of commodities are always (very) uncertain. In particular, biomass prices can be volatile depending on the underlying assumptions on scarcity (that drives up prices vs. costs) or strategies to increase availability (e.g., planting of degraded lands and increased agricultural productivity, which can push learning curves and lower the costs).

These primary assets can be distinguished as conventional fuels, biomass sources, and the ETS allowances projected costs. The data for the reference scenario used in this paper is composed of the following sources and presented in Table 21. First, conventional fuels prices projections are retrieved from POTEnCIA's Central Scenario database [77]. Then, the price projections of the bio-resources are based on ENSPRESO-BIOMASS reference scenario [45]. Finally, the ETS allowance cost projections are retrieved from two sources, the 2019 Netherland's Climate Energy Outlook [75] for the 2020–2030 period, and the CPB high-efficiency scenario projections [80] for the period 2030–2050.

F.3. Transition potentials

The potential assumed for technologies to develop has a large influence on the definition of the scenario. Many of these assumed potentials have an important influence in the determination of transitionary costs, notably, potentials for renewable energy sources (including biomass) and CO_2 storage. The reference scenario bases the storylines of these potentials accordingly with the ENSPRESO reference scenario for biomass [45] and the TNO's scenario 'towards a sustainable energy system for the Netherlands' [83]. Table 22 shows the assumed potentials for the reference scenario.

Appendix G. European power system generation capacities

The assumed installed electricity generation capacities play a crucial role in the definition of the scenario as it strongly influences the operation of flexibility assets and generation technologies in the Netherlands. Due to the lack of available high-decarbonization scenarios of installed capacities for the EU power system in 2050, a hybrid approach was used to select the assumed installed capacities for this study. The installed capapcities from 2020 to 2030 were extracted from a COMPETES studio based on 2018 TYNDP [13], the 2040 renewable energy installed capacities were extracted from 2020 TYNDP 'National Trends' Scenario [53],

Table 21
Costs assumptions considered in the Reference Scenario.

Commodity	Units	Values				Source
		2020	2030	2040	2050	
Coal	[$€_{2019}$/GJ]	3.0	3.7	4.1	4.4	[77]
Oil	[$€_{2019}$/GJ]	10	17	19	20	[77]
Natural gas	[$€_{2019}$/GJ]	7.1	10.3	11.4	11.8	[77]
Imported LNG	[$€_{2019}$/GJ]	7	9	9.7	10	[81]
Imported oil products	[$€_{2019}$/GJ]	12.5	21.2	23.8	25	[77]
Uranium	[$€_{2019}$/GJ]	0.8	0.8	0.8	0.8	[75]
Waste	[$€_{2019}$/GJ]	6.9	7.0	7.0	7.0	[82]
Imported biodiesel	[$€_{2019}$/GJ]	20	35	50	70	[83]
Imported biokerosene	[$€_{2019}$/GJ]	20	26	42	63	[83]
Manure	[$€_{2019}$/GJ]	0.1	0.1	0.1	0.0	[82]
Dry organic matter	[$€_{2019}$/GJ]	4.5	4.2	4.1	4.0	[82]
Grass crops	[$€_{2019}$/GJ]	9.5	8.7	8.4	8.2	[82]
Wood (crops, and others)	[$€_{2019}$/GJ]	16.9	16.9	16.9	16.9	[82]
Imported wood	[$€_{2019}$/GJ]	8.2	7.4	6.9	6.4	[82]
Sugars	[$€_{2019}$/GJ]	4.3	4.6	4.6	4.6	[82]
Starch	[$€_{2019}$/GJ]	15.9	21.3	21.5	21.9	[82]
Vegetable oil	[$€_{2019}$/GJ]	26.5	38.1	38.0	38.0	[82]
Imported vegetable oil	[$€_{2019}$/GJ]	30.5	43.7	43.7	43.7	[83]
ETS allowance	[$€_{2019}$/tonCO$_2$]	22	47	105	160	[75,80]

Table 22
Potential assumptions considered in the Reference Scenario.

Potential	Units	Values				Source
		2020	2030	2040	2050	
Nuclear power	[GW]	0.48	0.48	0	0	[83]
Offshore wind	[GW]	1.1	14	45	60	[83]
Onshore wind	[GW]	3.5	8	10	12	[83]
Solar PV fields	[GW]	1.1	5	15	30	[83]
Industrial Solar PV	[GW]	2.1	15	30	40	[83]
Residential Solar PV	[GW]	3.5	20	40	60	[83]
Geothermal Energy	[PJ/y]	10	50	125	200	[82]
Waste	[PJ/y]	46	55	64	74	[82]
Wet organic matter	[PJ/y]	3.7	4.3	5	5.6	[82]
Manure	[PJ/y]	72	72	72	72	[82]
Dry organic matter	[PJ/y]	7.4	7.6	8.8	9.5	[82]
Grass crops	[PJ/y]	14.2	27.7	25.7	23	[82]
Wood	[PJ/y]	60	80	100	120	[82]
Imported wood	[PJ/y]	20	120	220	320	[83]
Sugars	[PJ/y]	15.6	23	19.4	15.8	[82]
Starch	[PJ/y]	0.4	0.5	0.5	0.6	[82]
Vegetable Oil	[PJ/y]	0.1	0.4	0.1	0.1	[82]
Storage of CO$_2$	[MtonCO$_2$/y]	0	7.5	25	50	[83]

and the 2045 and 2050 capacities were extracted from IESA-Opt in a special pre-run defined for this purpose where the model was enabled for EU capacity planning. The resulting installed capacities used for the studio are visualized for all EU countries in Fig. 28 and are available in the reference scenario database. The interconnection capacities used for this study are reported in Table 23.

Currently, literature provides few scenarios for a highly decarbonized 2050 EU power system, and usually these scenarios are based on modelling outputs rather than detailed literary analysis of national published policies, paths, and targets. A more extensive analysis in this direction is required to strengthen the results hereby presented.

Table 23
Interconnection capacities amongst considered EU nodes in IESA-Opt.

		Interconnection Capacity [GW]						
Node	Connector	2020	2025	2030	2035	2040	2045	2050
Non-EU Balkans	Import from BU	5.15	6.45	6.45	6.45	6.45	6.45	6.45
	Import from IT	1.2	1.2	1.2	1.2	1.2	2.5	2.5
EU Balkans	Import from BN	4.15	5.3	5.3	5.3	5.3	5.3	5.3
	Import from IT	1.18	1.88	1.88	1.88	3.49	3.5	3.5
	Import from SK	2	2	2	2	2	2.31	3.5
	Import from AT	1.7	1.7	1.7	1.7	3	3	3
Baltic	Import from FI	1	1	1	1	1.58	2	2
	Import from PL	0.5	1	1	1	1	1	1
	Import from SE	0.7	0.7	0.7	0.7	1.5	1.5	1.5
Finland	Import from BT	1	1	1	1	1	1	1
	Import from SE	2.4	2.4	3.2	3.2	3.2	3.2	3.28
Italy	Import from BN	1.2	1.2	1.2	1.2	1.2	1.2	2.5
	Import from BU	1.23	2.03	2.03	2.03	2.03	2.03	4
	Import from AT	0.405	1.005	1.655	1.66	1.66	1.66	3
	Import from CH	4.24	5.29	5.29	5.29	5.29	5.29	9
	Import from FR	4.35	4.35	4.35	4.35	6.61	8	8
Portugal	Import from ES	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Spain	Import from PT	3.2	3.2	3.2	3.2	3.2	3.2	4.42
	Import from FR	2.8	5	8	8	8	8	11.22
Slovakia	Import from BU	2	2	2	2	2	2	3.5
	Import from CZ	1.8	1.8	1.8	1.8	1.8	1.8	1.8
	Import from PL	0.99	0.99	0.99	0.99	0.99	0.99	2
Czech Republic	Import from SK	1.1	1.1	1.1	1.1	1.1	1.1	1.21
	Import from PL	0.8	0.8	0.8	0.8	0.8	0.8	1.6
	Import from AT	0.9	0.9	1	1	2	2	2
	Import from DE	1.5	1.5	2	2	2.5	2.5	2.5
Poland	Import from BT	0.5	1	1	1	2	2	2
	Import from SK	0.99	0.99	0.99	0.99	1.95	2	2
	Import from CZ	0.6	0.6	0.6	0.6	1.2	1.2	1.2
	Import from SE	0.6	0.6	0.6	0.6	1.2	1.2	1.2
	Import from DE	0.5	2	2	2	4	4	4
Austria	Import from BU	1.7	1.7	1.7	1.7	1.7	1.7	2.02
	Import from IT	0.235	0.835	1.384	1.38	1.38	1.38	1.38
	Import from CZ	0.8	0.9	1.2	1.2	1.2	1.2	1.2
	Import from CH	1.2	1.7	1.7	1.7	1.7	1.7	1.7
	Import from DE	5	6	7.5	7.5	7.5	7.5	7.5
Switzerland	Import from IT	1.91	2.51	2.51	2.51	2.51	2.51	2.51
	Import from AT	1.2	1.7	1.7	1.7	1.7	1.7	1.7
	Import from FR	3.2	3.7	3.7	3.7	3.7	3.7	7
	Import from DE	1.586	3.286	3.286	3.29	3.29	3.29	3.29
France	Import from IT	2.16	2.16	2.16	2.16	2.16	2.16	2.16
	Import from ES	2.4	5	8	8	8	9.85	15
	Import from CH	1.3	1.3	1.3	1.3	1.3	1.3	1.3
	Import from IE	0	0.7	0.7	0.7	0.7	0.7	0.7
	Import from BE	1.8	2.8	2.8	2.8	2.8	2.8	2.8
	Import from DE	2.3	3.3	4.8	4.8	4.8	4.8	4.8
	Import from GB	4	7.4	7.4	7.4	7.4	7.4	7.4
Sweden	Import from BT	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	Import from FI	2.3	2.3	2.8	2.8	2.8	2.8	2.8
	Import from PL	0.3	0.6	0.6	0.6	0.6	0.6	0.6
	Import from DE	0.615	1.315	1.315	1.32	1.32	1.32	1.32
	Import from DK	2.44	2.44	2.44	2.44	2.44	2.44	2.44
	Import from NO	3.7	3.7	3.7	3.7	3.7	3.7	3.7
Ireland	Import from FR	0	0.7	0.7	0.7	0.7	0.7	0.7
	Import from GB	0.95	1.45	1.45	1.45	1.45	1.45	1.45
Belgium	Import from FR	3.3	4.3	4.3	4.3	4.3	4.3	7.3
	Import from NL	1.4	3.4	3.4	3.4	3.4	7	7
	Import from DE	1	1	1	1	1	1	1
	Import from GB	1	1	1	1	1	1	1
Germany	Import from CZ	1.586	2.1	2.6	2.6	2.6	2.6	2.6
	Import from PL	3	3	3	3	3	3	3
	Import from AT	5	6	7.5	7.5	7.5	7.5	7.5
	Import from CH	4	4.7	4.7	4.7	4.7	4.7	4.7
	Import from FR	1.8	3.3	4.8	4.8	4.8	4.8	9
	Import from SE	0.615	1.315	1.315	1.32	1.32	1.32	2.5
	Import from NL	4.25	5	5	5	7.83	10	10
	Import from BE	1	1	1	1	1	1	3
	Import from DK	2.78	4	4	4	4	4	4
	Import from NO	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Denmark	Import from SE	1.98	1.98	1.98	1.98	1.98	1.98	1.98
	Import from NL	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	Import from DE	2.5	4	4	4	4	4	4
	Import from NO	1.64	1.64	1.64	1.64	1.64	1.64	1.64
	Import from GB	0	1.4	1.4	1.4	1.4	1.4	1.4

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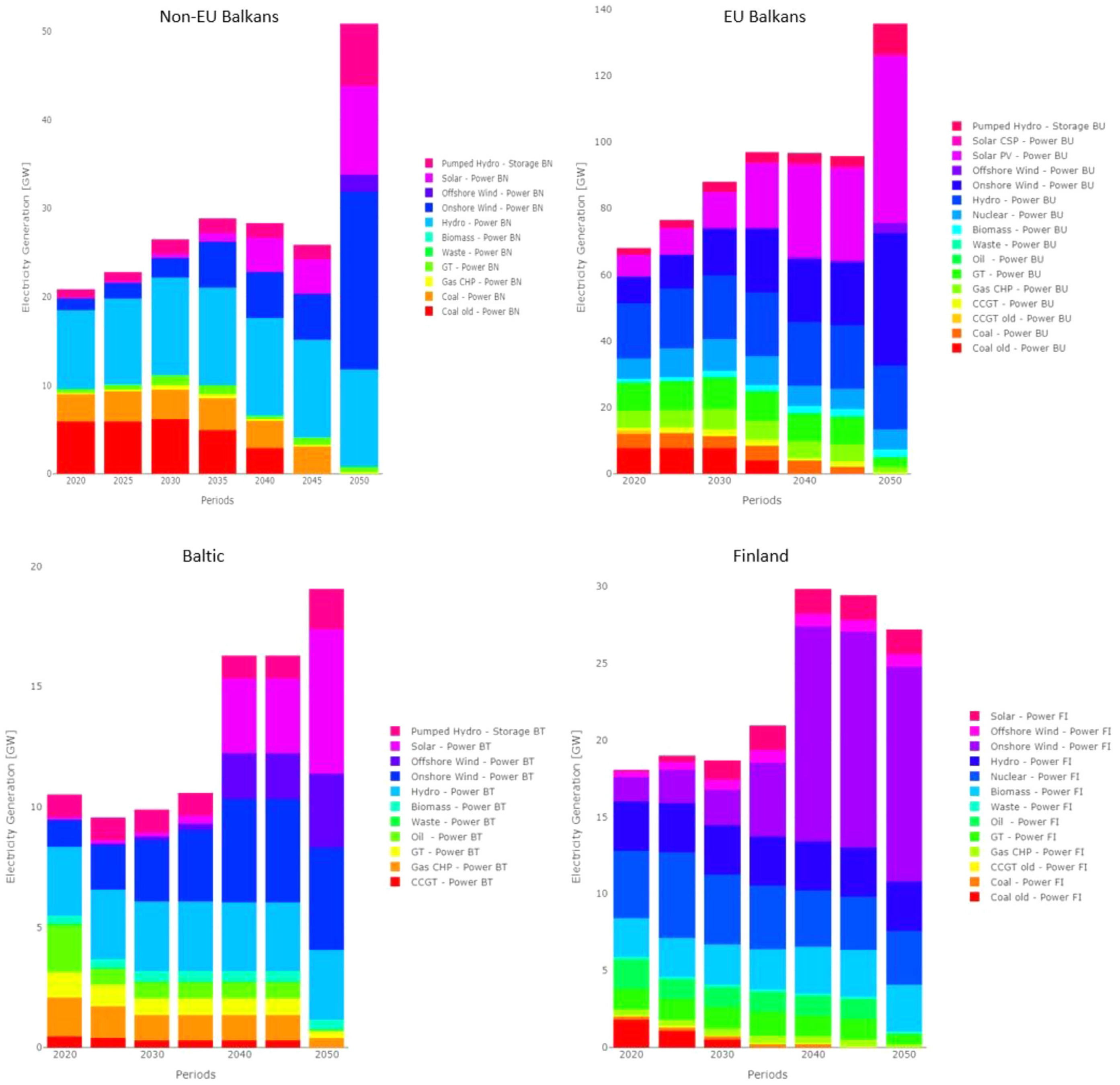
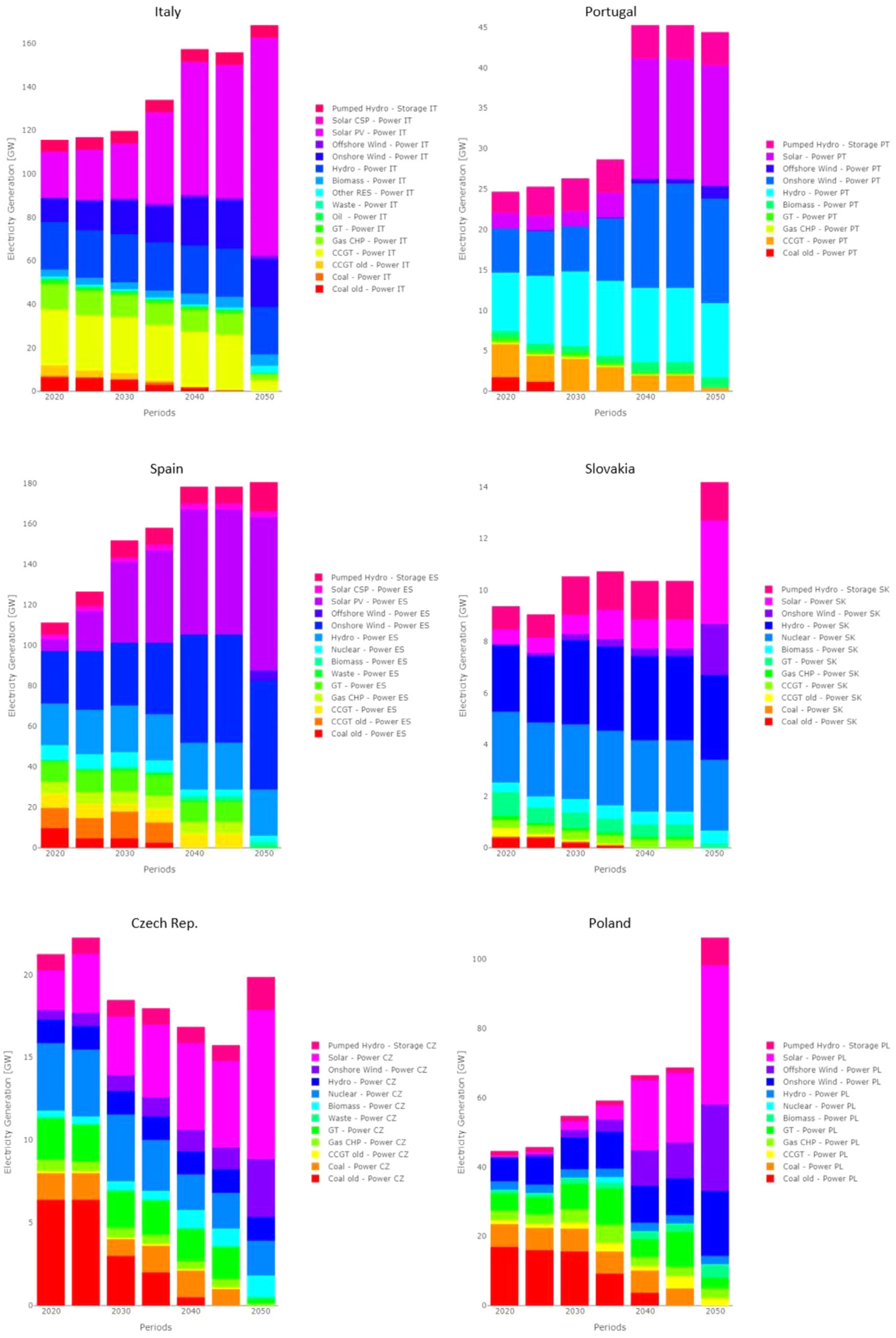


Fig. 28. Installed capacities evolution assumed for this study for all the 20 considered EU nodes in IESA-Opt.

Table 23 (*continued*)

Node	Connector	Interconnection Capacity [GW]						
		2020	2025	2030	2035	2040	2045	2050
Norway	Import from SE	3.995	3.995	3.995	4	4	4	4
	Import from NL	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	Import from DE	1.4	1.4	1.4	1.4	1.4	1.4	1.4
	Import from DK	1.64	1.64	1.64	1.64	1.64	1.64	1.64
	Import from GB	0	1.4	1.4	1.4	1.4	1.4	1.4
Great Britain	Import from FR	4	7.4	7.4	7.4	7.4	7.4	7.4
	Import from IE	0.58	1.08	1.08	1.08	1.08	1.08	1.59
	Import from NL	1	1	1	1	1	1	2
	Import from BE	1	1	1	1	1	1	1
	Import from DK	0	1.4	1.4	1.4	1.4	1.4	1.4
	Import from NO	0	1.4	1.4	1.4	1.4	1.4	3



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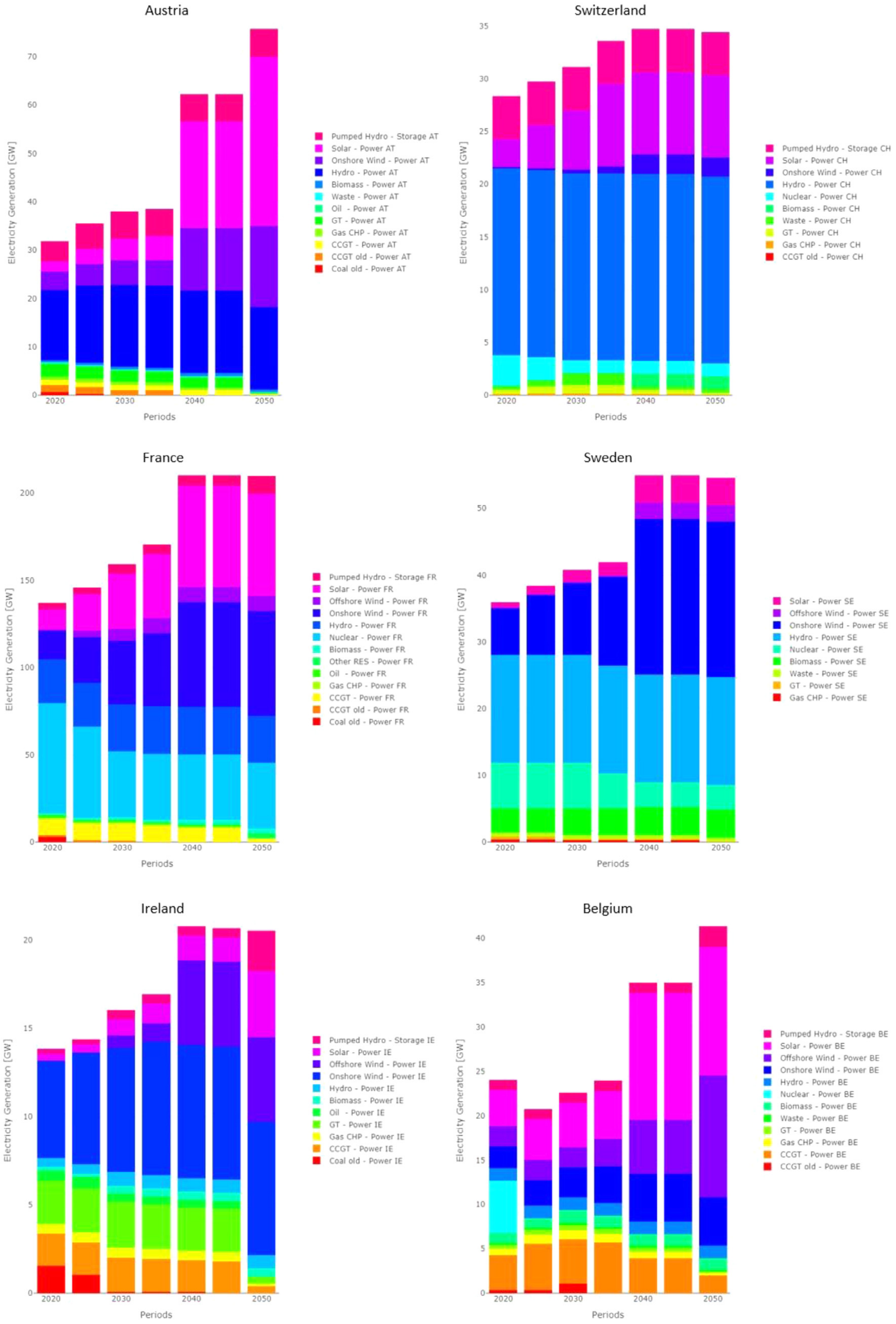

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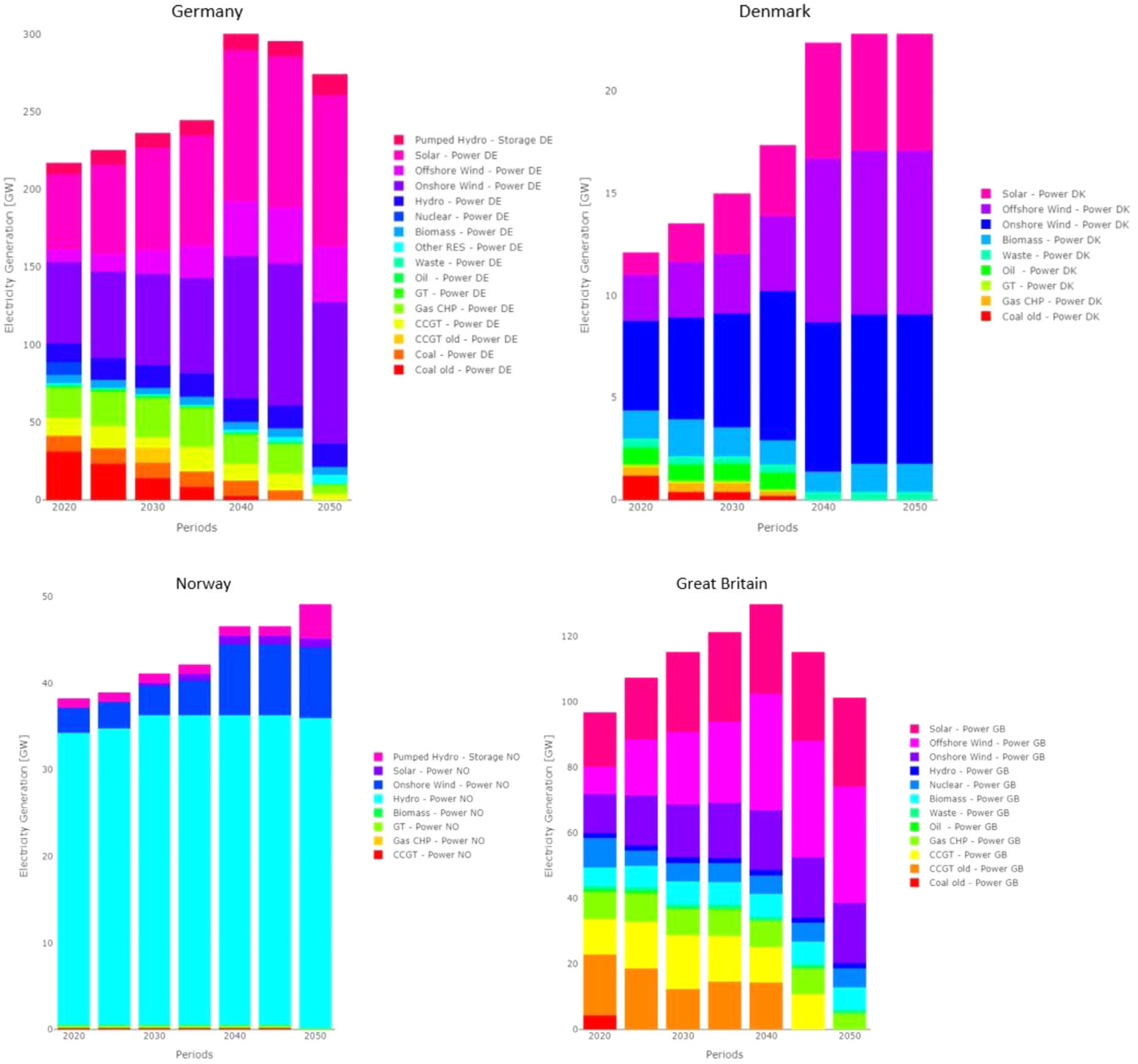

Fig. 28. Continued

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