OPERA: A New High-Resolution Energy System Model for Sector Integration Research

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Abstract

This article introduces and describes OPERA, a new technology-rich bottom-up energy system optimization model for the Netherlands. We give a detailed specification of OPERA's underlying methodology and approach, as well as a description of its multiple applications. The model has been used extensively to formulate strategic policy advice on energy decarbonization and climate change mitigation for the Dutch government, and to perform exploratory studies on the role of specific low-carbon energy technologies in the energy transition of the Netherlands. Based on a reference scenario established through extensive consultation with industry and the public sector, OPERA allows for examining the impact of autonomous technology diffusion and energy efficiency improvement processes, and investigating a broad range of policy interventions that target greenhouse gas emission abatement or air pollution reduction, amongst others. Two characteristics that render OPERA particularly useful are the fact that (1) it covers the entire energy system and all greenhouse gas emissions of the Netherlands, and (2) it possesses a high temporal resolution, including a module for flexibly handling individual time units. The simulation of the complete Dutch energy system and the ability to represent energy supply and demand on an hourly basis allow for making balanced judgements on how to best accommodate large amounts of variable renewable energy production. OPERA is therefore particularly suited for analyzing subjects in the field of system integration, which makes it an ideal tool for assessing the implementation of the energy transition and the establishment of a low-carbon economy. We outline several near-term developments as well as opportunities for future improvements and refinements of OPERA. One of OPERA's attractive features is that its structure can readily be applied to other countries, notably in Europe, and could thus relatively easily be extended to cover the entire European Union.

Keywords: energy system; sector integration; variable renewable energy; climate change mitigation; the Netherlands

1 Introduction

Under the Paris Agreement of December 2015 [1] all countries in the world have committed to drastically reduce their emissions of greenhouse gases (GHGs). Their Nationally Determined Contributions (NDCs) imply major changes in domestic energy systems, and particularly substantial decreases in the use of fossil fuels and large increases in the deployment of renewable energy technologies. Among the mitigation options available over the next couple of decades are a shift towards an electrification of the energy system, a circular use of CO_2 and the use of local renewable but often intermittent energy resources. A common feature of the energy transitions that individual countries will need to implement is an integration of sectors that thus far operated as nearly independent entities in national energy systems. Given the complexities of today's energy systems and the increasing linkages between sectors therein, the use of models that allow for *integrated* energy system analysis is a prerequisite. The usage of integrated energy system models can give insight into how future energy infrastructures may need to look like, in a way that models focusing on individual sectors cannot provide.

The OPERA (Option Portfolio for Emissions Reduction Assessment) model is a newly developed tool for integrated energy systems analysis for the Netherlands. The OPERA model has been successfully applied for cross-sectoral integration analysis for the Dutch government and within several Dutch research projects during the past several years. OPERA is unique in the sense that it covers the entire energy and GHG system of the Netherlands. It is an improved and more detailed successor of an earlier model used for similar purposes [2]. Thanks to its high time-resolution, OPERA is particularly suited for creating integral judgements on the role of electrification amongst a broad range of options in reducing GHG emissions, in an energy system with a gradually increasing share of variable renewable energy sources. To date, however, no comprehensive description of OPERA has been made available for either policy makers or the scientific community, even while the model has been used extensively already for national policy design in the Netherlands. This publication aims at filling this gap, and should compensate for the paucity of public information on the OPERA model thus far.

Section 2 of this article gives a general description of the methodology, scope and approach of OPERA. More details on the building blocks of the energy system covered in OPERA, as well as on how the model operates, are described in section 3. In section 4 we explain how linkages exist and/or can be established between OPERA and other energy models, and give a few examples of the type of output and insights that we are able to generate with OPERA. In section 5 we formulate some conclusions and indicate how we intend to further refine the OPERA model in the future, plus highlight that we could possibly apply the OPERA structure and setup to countries other than the Netherlands. We would thereby enable research on sectoral integration of energy systems across multiple countries simultaneously, especially in the European Union (EU).

2 Scope and approach of the model

The introduction of a model needs a description of the methodology, the kind of data to be able use the model and the application areas, all of these are described in this section.

2.1 Approach

OPERA is an energy system model structure that can in principle be used to analyze possible low-carbon futures for any region in the world, provided that the necessary input data are available. In its current implementation the model contains a comprehensive database specific for the Netherlands, and to this date it has only been applied in the Dutch context.

OPERA is a Linear Programming (LP) optimization model, which currently uses the interior point method to solve the LP set-up [3]. The model is written and solved in AIMMS [4]. It computes the cost-optimal energy and GHG system configuration, under specific constraints, by minimizing an objective function that expresses the total system costs for a given future year. In contrast to other energy system models, like MARKAL (e.g. Loulou et al. [5]), TIMES (for instance Loulou [6]), TIAM [7, 8], TIAM-ECN (for example [9, 10]), OSeMoSYS [11] and ESME [12], OPERA does not optimize over a time horizon, but rather for a single future year, for example 2030 or 2050. In other words, the model is static instead of dynamic. The objective function, *CT*, is given in Equation 1. The meaning of the symbols used in Equation 1 can be found in Table 1.

$$CT = \sum_{r,o,t} ATY_{r,o,t}\,\mathbf{T}_t + \sum_{r,o}(AY_{r,o}\mathbf{CV}_{r,o} + CAP_{r,o}(\mathbf{CC}_{r,o} + \mathbf{CO}_{r,o})) + \sum_{r,o,e} AEY_{r,o,e}\mathbf{P}_{r,o,e} \quad \text{(Eq. 1)}$$

Table 1 Symbols in Equation 1.

Variables		Parameters		Indices	
CT	Total system cost (M€)	**T**	Penalty on emissions	r	Region
AY	Activity (per year)	**P**	Price of energy carriers	o	Option
AEY	Activity per energy carrier	**CC**	Annualized capital investments	t	Emission type
ATY	Activity per emission type	**CO**	Fixed O&M cost	e	Energy carrier
CAP	Capacity	**CV**	Variable cost		

The options (o) indicated in Equation 1 include both energy technologies and non-energy related measures to reduce emissions. OPERA is a technology-rich model. It contains around 500 technologies that cover the whole technology chain from production to end-use demand services (the only exception are mining and import processes other than electricity, which are not explicitly modeled). Primary sources such as crude oil are simply assumed to be available at a specified price. The model represents all technologies that convert primary into secondary sources, such as refineries in the case of crude oil.

The technologies and processes considered in the current version of OPERA are only those that directly contribute to the national GHG accounting of the Netherlands. Aviation and international navigation are thus excluded from the model as energy services demands. On the other hand, energy losses and process emissions from transforming crude oil to jet and marine fuels *are* included. Since the current model only considers emissions from Dutch territory, in line with guidelines from the Intergovernmental Panel on Climate Change [13], emissions due to land use change, cultivation and international transportation of imported biomass are not included.

2.2 Key entities

The OPERA model database contains data about either products, options, sectors or regions. Products cover all potential inputs and/or outputs of technologies, and are grouped into the following categories:

- **Primary energy carriers**; available from outside the energy system such as fossil fuels, uranium, or solar and wind resources.

- **Secondary energy carriers**; produced from primary energy carriers and used in the energy system, such as hydrogen, electricity and heat.
- **Non-energy products**; necessary for an adequate description of the energy system, such as steel, ammonia and other chemicals.
- **Emissions**; including all GHGs from energy conversion and non-energy activities, as well as particulate matter (PM), acidification matter (AM) and non-methane volatile organic compounds (NMVOC) from energy conversion technologies.
- **Captured CO_2**; labeled in the model as a separate product to make sure that CO_2 storage potentials are not exceeded and that stored CO_2 is not released into the atmosphere.

Options are the working horses of the model, converting input to output products. In cases not related to energy, they reduce emissions. Options are specified by investments, variable and fixed O&M costs, efficiencies and emissions. A more detailed description of the different types of technologies in OPERA can be found in section 3.4. OPERA includes all main sectors of the economy: households, services, agriculture, industry, transport and energy supply. Some sectors like industry are divided in subsectors. For an overview of all demand sectors currently covered by OPERA, see Table 2. OPERA allows for subdividing the geographical target area, or region, in smaller (sub-)regions, as described in more detail in section 3.2.

2.3 Application areas

The OPERA model is used for three kinds of applications: formulating policy advice, obtaining insight into the role of groups of technologies in meeting specified energy and environmental targets, and analyzing the effect of including or excluding certain components of the energy system or varying the spatial or temporal resolution of the model.

In the first field of applications, the model has been used to investigate the consequences of certain policy choices by setting specific emission or energy targets for the Netherlands in the medium term [14], and to give insight into how the Dutch energy system could evolve if emission reductions are realized that are in line with the Paris Climate Agreement [1], as reported in Ros and Daniëls [15]. In these studies sensitivity analyses have been performed on some of the most uncertain factors and assumptions in our model, such as the availability of biomass, the maximum potential for Carbon dioxide Capture and Storage (CCS), wind and solar energy potentials, and the willingness to use nuclear energy. For all different targets and sensitivity cases OPERA gives insight into how a cost optimal energy system could look like, and what parameters affect the final energy mix and emission reduction. This information, while not directly indicating what policy instruments and market structures are needed, can be used to evaluate the efficacy of envisioned policies to achieve the desired targets in a cost-efficient way.

Examples of the second area of application are integral analyses performed for power-to-gas technologies [16] and flexibility options [17]. Circumstances were investigated under which these technologies or options would become relevant for matching energy supply and demand. In these two studies the analysis was undertaken for the entire energy system, including technologies and options that currently play a negligible role, but that might become essential in the medium to long term.

In the third domain of application, OPERA has been used to analyze the effects of increasing the spatial and temporal resolution of the representation of the energy system. In de Joode et al. [18] the model was refined with a regional subdivision. This subdivision was realized by defining a number of stylistic regions representing localized demand and possibilities for decentral supply of energy services. This provided a better understanding of the consequences of moving towards a more decentralized energy supply system, and yielded insight into the different interlinkages within the energy system. OPERA has also been used to test the effect of different levels of temporal resolution within a year, which has improved our understanding of the implementation of variable renewable energy sources (VRES) in the Dutch energy system. Insights in the effects of higher time resolutions might be of particular relevance for energy system models that have a wider geographical scope and/or longer time horizon than OPERA.

One of the strengths of OPERA over other energy system models is that it possesses a high temporal resolution within a year. This can be flexibly defined by the modeler at the start of a scenario run without requiring additional input data. A high time resolution is important for an integral assessment of the role of electrification technologies in all sectors in the presence of large amounts of VRES supply. Most other energy system models have a broader geographical scope and a longer time horizon, which comes at the cost of time detail within a year. Models exist with a higher time resolution than OPERA, i.e. on an sub-hourly temporal basis, but they typically only cover the electricity sector or electricity and district heating [19]. A shift towards electrification of sectors currently mostly not relying on electricity (such as industry and transport) falls outside the scope of these models and can only be assessed via additional exogenous scenarios. Another added value of OPERA is its ability to use a significant level of detail from the official Dutch National Energy Outlook as baseline (see section 4.1).

3 Detailed model description

The most important elements of OPERA are detailed in this section.

3.1 Demand

Demand for energy is represented in OPERA via energy services (see Table 2). In most cases final energy demand is given as exogeneous input. In order to allow maximum flexibility, demands can also be expressed in the units that best suit the nature of each energy service. For example, the most straightforward determinant of road transport energy demand is the need for mobility expressed in total amount of kilometers driven yearly. Therefore the unit billion vehicle kilometers (B(v)km) is used for road freight and passenger vehicles, instead of the corresponding final electricity and heat demand in petajoules (PJ). Due to unavailability of input data, the remaining energy services in the transport sector (buses, motorbikes, trains, inland shipping and aviation, which only account for a small fraction of total demand) are grouped together in one single entity, for which the demand is expressed in PJ. These remaining subsectors can be singled out whenever input data becomes available.

Table 2 Energy service demands in OPERA; final energy demand is specified for both electricity and heat.

Sector	Energy Service Demand	Unit
Households	Final energy demand	PJ
Services	Final energy demand	PJ
Services	Mobile machinery	PJ
Transport	Road passenger cars	B(v)km[a]
Transport	Road freight	B(v)km
Transport	Road passenger vans	B(v)km

Sector	Energy Service Demand	Unit
Transport	Remaining final energy demand	PJ
Agriculture	Final energy demand	PJ
Agriculture	Mobile machinery	PJ
Industry	Steel production	Mt
Industry	Fertilizer (ammonia) production	Mt
Industry	Mobile machinery	PJ
Industry	Municipal solid waste incineration	PJ
Industry	Chemicals	PJ
Industry	Remaining final energy demand chemicals	PJ
Industry	Remaining final energy demand metals	PJ
Industry	Remaining final energy demand ETS	PJ
Industry	Remaining final energy demand non-ETS	PJ

[a] B(v)km = billion vehicle km.

3.2 Regions

From the start of the development of OPERA a regional dimension was added to all input parameters, variables and constraints. Currently it is not possible yet to provide regionally specific data directly. In the EDGAR project [18] input data were allocated to regions via distribution keys. Instead of a split according to geographical boundaries, a breakdown according to energy-related activities and potentials was adopted. Three stylistic regions were covered: rural, urban and industrial, complemented with a fourth region which represents large scale energy supply and the transmission grid. The main aim of including these different types of regions was to analyze interdependencies between different energy network levels and the differences in regional technology portfolios when going to deep GHG emission reductions.

3.3 Time-slices

OPERA explicitly deals with the need to achieve a match between energy supply and demand at any moment in time. For this purpose, supply and demand are provided as input to the model as hourly profiles (see section 3.4), for a whole year, theoretically enabling the user to run the model on an hourly basis. Running the model with an hourly resolution, however, is impractical (if not impossible) because of the exceedingly high computation capacity and time requirements. In order to achieve a suitable compromise between temporal resolution and computation time, the hours of a year can be grouped into a set with an arbitrary number of elements, called time-slices.

Relations between the activity and the capacity of an option at each time-slice, *ts*, are given in Equations 2 and 3.

$$A_{r,o,ts} \leq \mathbf{AF}_{r,o,ts}^{max}\mathbf{C2A}_o\mathbf{Y}_{ts}CAP_{r,o}, \ \forall_r, \forall_o, \forall_{ts} \quad \text{(Eq. 2)}$$

$$A_{r,o,ts} \geq \mathbf{AF}_{r,o,ts}^{min}\mathbf{C2A}_o\mathbf{Y}_{ts}CAP_{r,o}, \ \forall_r, \forall_o, \forall_{ts} \quad \text{(Eq. 3)}$$

where

$A_{r,o,ts}$ = Activity of option *o* in region *r* per time-slice *ts*
$\mathbf{AF}_{r,o,ts}^{max}$ = Maximum availability in time-slice *ts*, [0,1]
$\mathbf{AF}_{r,o,ts}^{min}$ = Minimum availability in time-slice *ts*, [0,1]
$\mathbf{C2A}_o$ = Conversion factor from capacity units to activity units of option *o*
$\mathbf{Y}_{ts}$ = Fraction of hours in a year assigned to time-slice *ts*

and $CAP_{r,o}$ is the capacity variable given in Table 1.

The relation between the activity for the whole year, AY (see Table 1), and the activity per time-slice is:

$$AY_{r,o} = \sum_{ts \epsilon TS} A_{r,o,ts}\,,\ \forall_r, \forall_o \quad \text{(Eq. 4)}$$

in which *TS* is the collection of all time-slices.

The allocation of hours into time-slices relies on the idea that hours with a similar character can be grouped together, without significantly affecting the level of insight in the final results. In the Appendix a description is given how hours can be assigned to different time-slices in practice. The user interface of the OPERA model includes a series of standard static and dynamic time-slice allocation mechanisms. Experience so far [16–18] suggests that in order to adequately capture the flexibility requirements of the energy system, a dynamic algorithm as described the Appendix with at least 32 time-slices is needed. So far, calculations with up to 432 time-slices have been used in model runs on a laptop without incurring excessive computation times.

Once the optimization is executed it is possible to transform the optimal quantities at time-slice level back to an hourly resolution, using the correct chronological order. This was applied in the FLEXNET project, in which a post-optimization analysis was performed to quantify the role of flexibility options [17]. The sequence from using hourly based profiles, applying time-slices in the optimization, and doing additional analysis on an hourly basis is illustrated in Figure 1.

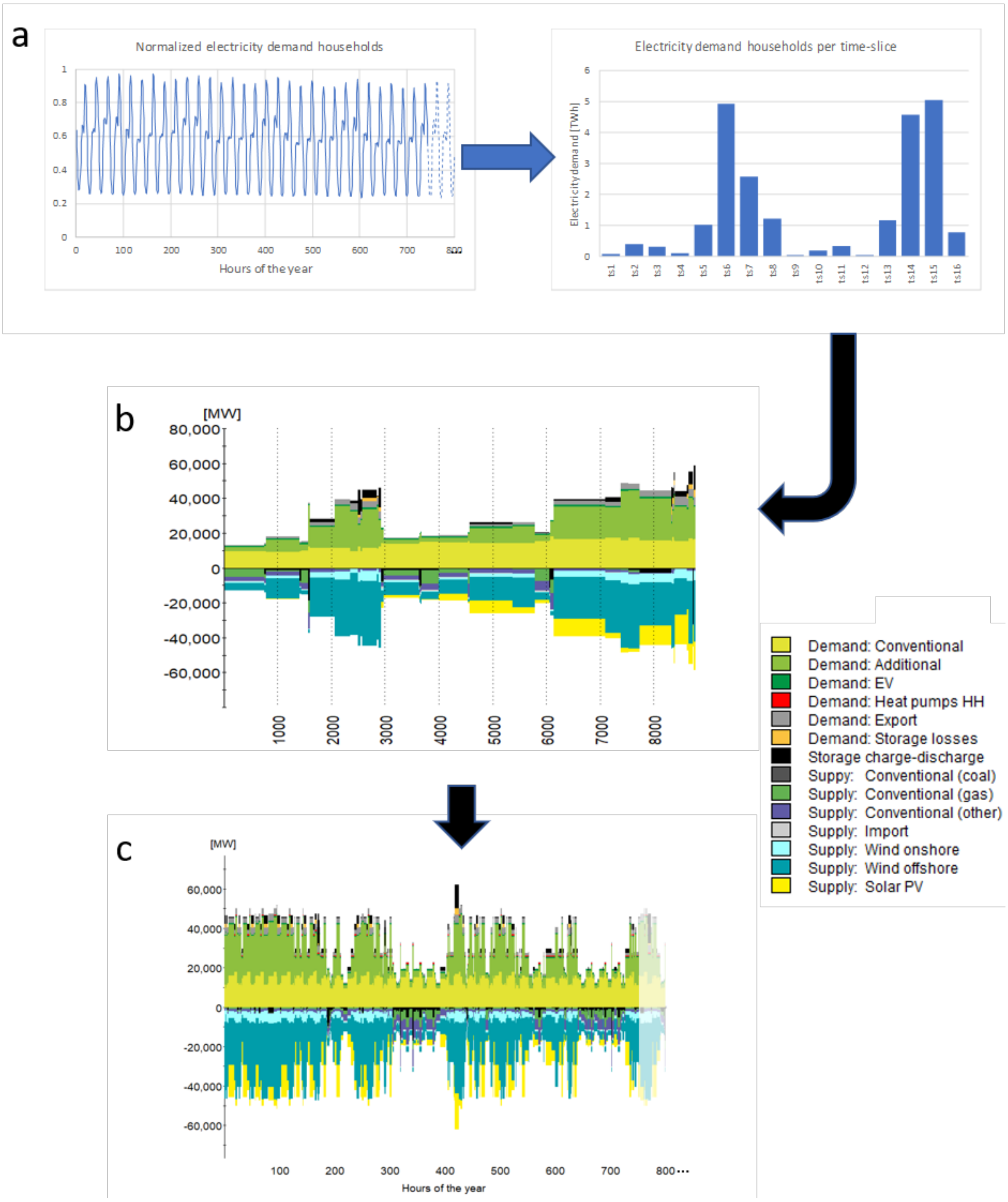

Figure 1 The use of different time resolutions in OPERA: a) hourly demand profiles are transformed in the pre-processing phase into demand per time-slice; b) optimization is executed using time-slices; c) results on time-slice basis are transformed into hourly results for additional analysis in the post-processing stage.

3.4 Demand and supply profiles

OPERA uses hourly profiles as input to the model. This makes the model more flexible than providing profiles per time-slices directly, since it allows the user to change the amount of time-slices as well as the way hours are allocated to time-slices. For demand profiles the input should be such that the sum over the hours results either in unity or the total yearly demand. For supply profiles the value per hour represents a maximum availability, similar to the maximum availability for time-slices as given in equation 2.

Exogenous profiles for energy service demands are used whenever data is available. For energy supply technologies only profiles of solar and wind energy are explicitly provided. In case the profile of an energy service demand is not known, a flat profile is assumed. For electricity demand, known sectoral profiles are subtracted from the aggregated national profile. The remainder is used as the hourly demand profile for sectors for which a specific demand profile is lacking.

The model has the possibility to deviate from a fixed profile if a maximum deviation percentage is given. This allows technologies to operate at a higher activity level in time-slices for which the marginal costs of electricity are low, and at a lower activity level during time-slices for which the marginal costs of electricity are high. It is also possible to put additional constraints on this flexibility. For example for electrical vehicles (EVs), there is flexibility in the moment of charging (but only within the same day, so that postponing charging to other days is not possible). This flexibility means that the model implicitly deals with demand response. With the exception of solar and wind energy, supply technologies have the flexibility to operate between availability zero and 100% for any time-slice. Solar and wind energy also have the flexibility to be operated at zero production for any time-slice, but their maximum availability is constrained by weather conditions as specified in their initial profiles.

For solar energy, the maximum availability profile is derived from historical regional specific hourly irradiation levels. For wind energy the profile is derived from historical regional specific hourly wind speeds. Such wind speeds are subsequently converted into wind speeds at hub height, followed by the application of a representative power velocity curve [20, 21].

The user has to make sure that all profiles correspond to the same representative reference year. This means that the same reference year for all demand and supply profiles needs to be used. Usually, a representative year with respect to weather and temporal distribution of service demands is chosen. More extreme years might be relevant if the user wants to test the energy system under certain situations (e.g. a very cold winter or a much less windy year than average).

3.5 Options

In general, options convert input into output products. Most options can be identified by a particular type of installation, plant or device. However, occasionally options represent a collection of installations, for example, the aggregate of all installation of a (sub)sector. In this case, the net balance of input and output products is used. Each option is assigned to a single sector. This allows for sector specific technology costs and operations. For example, there are specific types of air heat pumps in households and in the services sector.

There are some type of options that require some additional attention:

- **Final energy demand options**; include only either heat or electricity as input, there is no output product.
- **Energy savings options**: reduce final demand. This is modeled as a negative energy demand.
- **Energy storage options**; uncouple the moment of production of an energy carrier and the consumption of this energy carrier. Storage options are described in more detail in 3.6.

- **Non-energy GHG reduction options**; do generally not consume or produce energy (though there are exceptions), but do reduce GHG emissions. For example, an option labeled 'Lowering the protein content of grassy products', results in lowering the emissions of N_2O in the agriculture sector.
- **Energy network options**; transport energy from one location (or option) to another location (or option). Energy networks are described in more detail in 3.7.

Options can furthermore be distinguished by being either fixed or flexible. Fixed options have for one unit of activity the same quantity of each input and output product, for each time-slice. The input/output ratios can only differ per calculation year and are determined exogenously. Flexible options, in contrast, are characterized by ratios of input and/or output products which are not pre-determined but are an outcome of the optimization and can differ per time-slice. OPERA makes a distinction between three kinds of flexible options:

- **Bandwidth options:** have inputs and/or outputs ratios that can change within a certain bandwidth. An example is a flexible CHP unit, where the output can switch from only heat to partial heat and partial electricity.
- **Hybrid options**; are modelled by two separate options, that can operate independently. The capacities are coupled either via a fixed or flexible ratio. An example is a hybrid heat pump. This technology consists of a heat pump part, and a gas boiler part. The ratio between the capacities of the two options is such that it is possible to produce heat at all time. Since the activities are uncoupled the relative activity of both separate parts can differ per time-slice, but it is not possible that both options have maximum activity at the same time.
- **Extreme mode options**; can run in two extreme modes and anything in between. These options are modeled by two separate options, each one representing one side of the extreme, that have exactly the same capacity. All fixed cost components are only counted once. The character of the inputs and outputs can differ per modus. An example is a generation IV nuclear energy plant with integrated hydrogen production. This plant can produce solely hydrogen in one modus and hydrogen and electricity in the other modus.

3.6 Description of storage

Energy storage options are different from other demand and supply options, since they are able to transfer energy from periods when there is excessive production to periods when there is a shortage. Storage options fulfill the following criteria:

- The amount of stored energy (storage level) should always be greater than or equal to zero;
- The storage level before discharge should always be greater than or equal to the energy amount that is discharged;
- It is possible to transfer energy from one time-slice to other time-slices;
- There is a storage capacity in terms of energy stored;
- The processes of charging and discharging are characterized by a certain capacity (i.e. with unit kW);
- Energy losses over time are included;
- A minimum duration for charging/discharging is specified.

The above criteria are achieved in the model by splitting a storage technology in three separate subunits, which are treated as three separate options. Each storage technology consists of: a charging unit, a storage unit and a discharge unit. The charge and discharge units behave as any other option in OPERA. The storage unit is different from other options in that (i) its capacity is modelled as a storage level (i.e. with unit kWh), (ii) it can switch from demanding (charging mode) in one time-slice to producing (discharging mode) in another time-slice, and (iii) it operates across time-slices.

Two other specifics require further clarification. First, since OPERA uses time-slices there is no natural chronological order, like one has, for example, in a model that operates on an hourly basis. In a model in which the time steps are chronological, the value of the storage level can be transferred from one time step to the next, correcting for (dis)charging and energy losses. In case of time-slices, this is approximated by considering all hours of time-slice ts_x that are preceded by an hour from other time-slices, ts_y, corrected for the frequency time-slice ts_x is preceded by hours from other time-slices. In terms of equations this becomes:

$$SL^{start}_{r,o,ts_x} = \sum_{ts_y \epsilon TS} \mathbf{S}_{ts_y ts_x} SL^{end}_{r,o,ts_y} (1 - \mathbf{L}_o),\ \forall_r, \forall_o, \forall_{ts_x} \quad \text{(Eq. 5)}$$

$$\mathbf{S}_{ts_y ts_x} = \frac{\sum_{h \epsilon H} \mathbf{C}_{h-1,ts_y} \mathbf{C}_{h,ts_x}}{\mathbf{F}_{ts_x}},\ \forall_{ts_x}, \forall_{ts_y} \quad \text{(Eq. 6)}$$

where

SL^{start}_{r,o,ts_x} = Start storage level of option *o* in region *r* for time-slice ts_x

SL^{end}_{r,o,ts_y} = Final storage level of option *o* in region *r* for time-slice ts_y

$\mathbf{L}_o$ = Energy losses of option *o* per hour

h = Hour

$\mathbf{C}_{h,ts_x}$ = Binary parameter indicating if hour *h* is present in time-slice ts_x

$\mathbf{F}_{ts_x}$ = Frequency parameter. The number of times an hour of time-slice ts_x is preceded by an hour from another time-slice.

$\mathbf{S}_{ts_y ts_x}$ is the fraction of energy from time-slice ts_y that is transferred to time-slice ts_x. It is subject to the following two equations:

$$\mathbf{S}_{ts_x ts_x} = 0,\ \forall_{ts_x} \quad \text{(Eq. 7)}$$

$$\sum_{ts_y \epsilon TS} \mathbf{S}_{ts_y ts_x} = 1,\ \forall_{ts_x} \quad \text{(Eq. 8)}$$

Second, storage levels are always greater than or equal to zero. At time-slice level this is easily guaranteed by requiring the storage levels to be non-negative. However, this does not guarantee that storage levels are non-negative for each hour. It has indeed been observed, by transforming results to an hourly basis, that storage levels can be negative. This problem can be solved by requiring storage levels to be non-negative per hour as well. To avoid an excessive increase in computation time this has been tackled by enforcing non-negative storage levels on a daily instead of hourly basis. Extensive testing has confirmed that in most cases this approximation yields acceptable results, i.e. for the largest part of the year storage levels are equal to or greater than zero, except for a few hours where small negative values are observed.

3.7 Energy networks

In OPERA, energy networks are provided for electricity, heat, natural gas and hydrogen. For an adequate modelling of these energy carriers it is important that their transport via energy networks is represented. Reasons for inclusion of the energy network are: the significant costs they can have for the system, the connection of different options to different voltage or pressure levels, and the substantial energy losses that energy carriers can have over the energy network.

There are two variables that are used to represent the transport of energy:

- *FlowInterRg*: representing the transport of an energy carrier from region A to region B.
- *FlowIntraRg*: representing the transport of an energy carrier from option A to option B, within the same region.

Via the index domain of the second variable a network within a region can be built describing the allowed connections between options. For example, solar PV in the household sector can only be connected to equipment in the household sector and to the low voltage electricity grid.

OPERA makes a distinction between two kinds of network options: those linking regions and those transferring the energy carrier to another voltage or pressure level. Examples of the first kind are pipes and cables. Examples of the second are transformers and connectors. These transformers and connectors do not connect regions, therefore only *FlowIntraRg* applies. Transforming to another energy network level requires no distinct energy carrier. The level at which the energy carrier is applied is determined by the allowed connections between network, supply and demand options. For example solar PV in the household sector, as described above, only operates at the low voltage level. An illustration of the connections at different network levels is given in Figure 2.

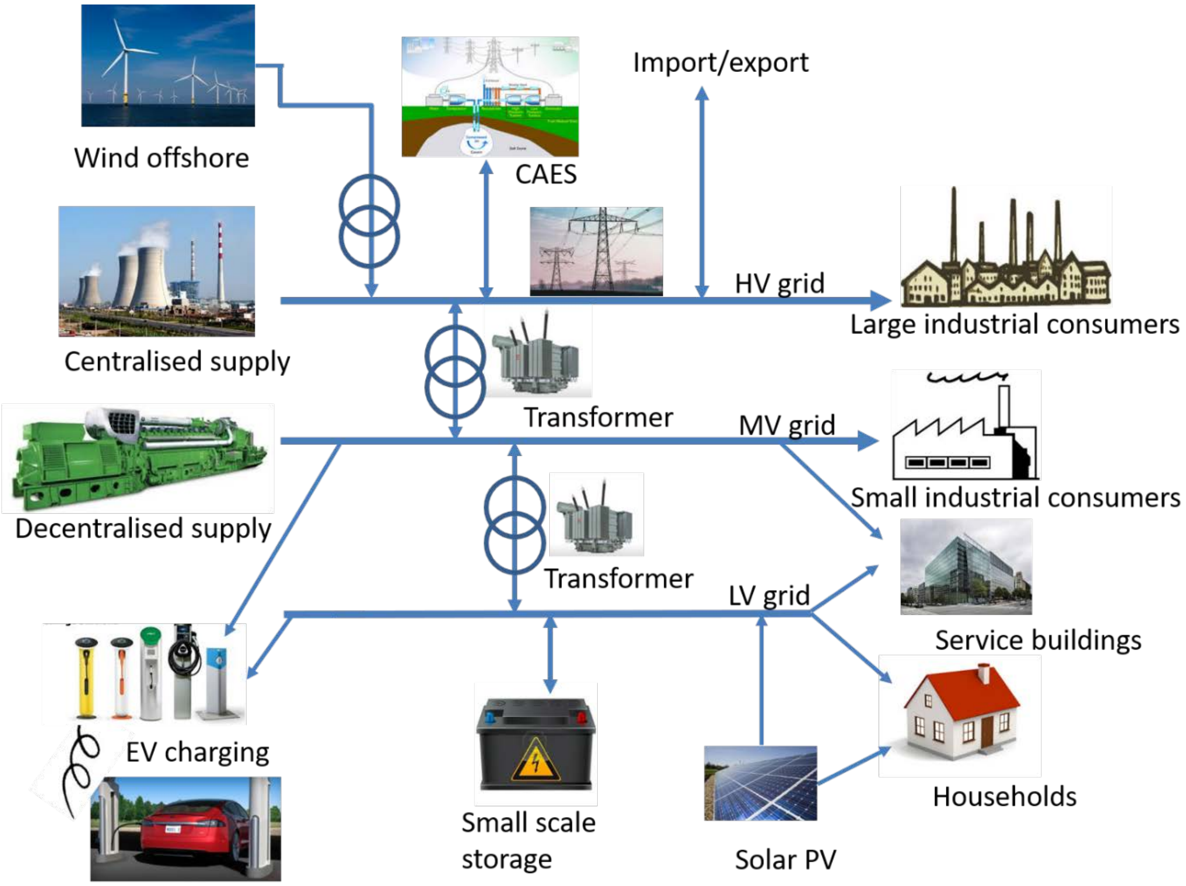

Figure 2 Illustration of the electricity network and its different network levels [18].

By default OPERA assumes there is a connection between options that operate in the same subsector. For example, a chemical process that produces heat as byproduct is automatically connected to another chemical process that needs heat as an input. The user of the model has the possibility to overrule such automatic connections by specifically disconnecting options. The basic characteristics of the available energy networks in OPERA are presented in Table 3.

Table 3 Basic characteristics of the available energy networks in OPERA.

Main energy carrier	Operating levels	Connects regions	Other energy carriers
Electricity	-Low Voltage -Medium Voltage -High Voltage	Yes	No
Natural gas	-Low Pressure -Medium Pressure -High Pressure	Yes	Yes, admixing of hydrogen, upgraded biogas and bio SNG
Hydrogen	-High Pressure -Low Pressure distribution -Transport filling stations	Yes	No
Heat	Heating network	No	No

3.8 Emissions

OPERA covers CO_2 as well as all other main gases that make a non-negligible contribution to the current total level of GHG emissions. Furthermore, the model contains air pollutants. The emissions that are covered by OPERA are specified in Table 4. The model may contain mitigation options for all emission types, but in the current version there are no options specifically designed for reducing air pollutants.

Table 4 Emissions covered by OPERA.

Emission type	Emission category	Unit
CO_2	GHG	$MtCO_2$
Methane (CH_4)	GHG	$MtCO_2eq$
Nitrous Oxide (N_2O)	GHG	$MtCO_2eq$
Fluoride gases (hydrofluorcarbons, perfluorocarbons and SF_6)	GHG	$MtCO_2eq$
PM_{10}	PM	kt
$PM_{2,5}$	PM	kt
NO_x	AM	kt
SO_2	AM	kt
Ammonia	AM	kt
NMVOC	NMVOC	kt

Emission reduction targets can be set per individual type, but also per emission category. The general form of the corresponding constraint in OPERA is given in Equation 9:

$$\sum_{r,o} ATY_{r,o,t} \leq \mathbf{TA}_t, \ \ \forall_t \quad \text{(Eq. 9)}$$

Where $\mathbf{TA}_t$ is the target for emission type or category t and the activity per emission type, $ATY_{r,o,t}$, is calculated as:

$$ATY_{r,o,t} = \sum_e AEY_{r,o,e}\, \mathbf{EF}_{t,e}\left(1 - \mathbf{EC}_{o,t}\right) - AY_{r,o}\mathbf{N}_{o,t}, \ \forall_r, \ \forall_o, \ \forall_t \quad \text{(Eq. 10)}$$

In the last equation, $AEY_{r,o,e}$ is the activity level per energy carrier as given in Table 1. $\mathbf{EF}_{t,e}$ is the emission factor for emission type t and energy carrier e. The factor $\mathbf{EC}_{o,t}$ allows for an option specific correction to the default emissions for energy carrier e. For example, the default particulate matter emission factor of woody biomass needs to be corrected depending on the type of conversion technology. The factor $\mathbf{N}_{o,t}$ applies in case a there is an emission effect which is not related to an energy carrier, such as non-energy related emissions of fluoride gases. This factor is also used in the model to correct for CO_2 that is captured and stored (CCS).

3.9 Other system and user constraints

To be able to get a realistic representation of the Dutch energy system and to have the flexibility to easily test the effect of additional restrictions on the energy system, OPERA contains several additional constraints that we briefly describe here. It is possible to introduce additional targets other than those for emissions as described in section 3.8. For example, a renewable energy target, according to the definitions of the EU Renewable Energy Directive [22] can be set. Furthermore, energy savings related targets can be put in place: a cap on primary energy consumption and on final energy consumption. Instead of a target, a tax can also be applied. Constraints on the capacity and/or yearly activity of specific options or subsets of options can be applied. Via this route renewable energy potentials can be enforced. For example, the potentials of wind offshore energy. Likewise it is possible to put constraints on the consumption of specific energy carriers or a group of energy carriers, such as limits on the quantity of biomass. Such maxima can apply per type of biomass, on imports and/or on domestic biomass. To make the model of more relevance for assessing policy implications it can be convenient to impose sector specific restrictions. For example, in the Netherlands there is currently a lively debate about natural gas-free heating of houses and other buildings. The model allows for imposing such restrictions via sector specific limits on options and/or energy carriers. The Netherlands has an extensive natural gas infrastructure. This network can also be partially used for hydrogen transportation and distribution. The model includes a constraint that restricts the admixing of hydrogen in the natural gas network to a maximum percentage. Sometimes there are logical relations between the extent to which a certain option is used and the capacity of other (sub)options. An example of such a relation is the total storage volume of EVs and the total number (capacity) of vehicles. Excluding this relation might result in an unrealistically large usage of the storage capacity of batteries in EVs.

4 Other models and outputs

Since models have their strengths, weaknesses and often a dedicated purpose, (soft) linking of models offers a possibility to do analysis which go beyond the capabilities that a single model offer. Examples of linkages between models have been described in the past extensively: linkage of an economic optimization model and a climate model [23, 24], linkage of an energy system model and a power market model [25], and linkage of a macro-economic model and an energy system model [26] represent good examples. Linkage of OPERA to other models has also been established as described in subsections 4.1 and 4.2.

4.1 Dutch National Energy Outlook Modelling System

OPERA is soft linked to the Dutch National Energy Outlook Modelling System (NEOMS) [27, 28], which is used for compiling the Dutch National Energy Outlook [29, 30]. NEOMS consists of several detailed sectoral models which are calibrated on the basis of statistics (in particular the Dutch Central Bureau of Statistics, [31]) and on the insights of many energy experts from several Dutch institutions. Before 2014 the NEO appeared roughly every five years. Since 2014 it appears on an annual basis, and its direct relevance for policy makers has increased considerably. Given the role played by many stakeholders and analysts in operating NEOMS and determining its inputs, the NEO provides broadly accepted baseline scenarios, which are based on both existing and proposed policies, as well as on varying socio-economic and techno-economic developments. OPERA uses the NEO scenarios developed by NEOMS as input, that is, as its reference energy system. Particularly, several kinds of information from NEOMS are fed into the OPERA database:

- Quantities of energy service demand.
- Emissions.
- Prices of primary energy carriers.
- Input-output ratios of energy options actually present in NEOMS.

An example of the latter are the inputs and outputs of an internal combustion engine for passenger cars. Many features of the NEOMS reference system can thus be reconstructed by OPERA, including the GHG emissions levels, the overall energy balance and the technology deployment. The NEO baseline is used to compare the scenario results of OPERA under various energy system conditions and policy instruments in terms of e.g. additional cost requirements and changes in energy demand and supply and provides statistical data to calibrate OPERA

4.2 Electricity market model

So far, the OPERA model structure has been restricted to model runs for the Netherlands. Energy sources from outside the Dutch energy system are considered to be available, either in a limited fashion (for e.g. biomass and biofuels) or in an unlimited way (such as for fossil energy carriers); the hourly profile in this respect bears no particular relevance. For the Dutch energy system import and export of electricity is very important, in particular in the context of growing shares of variable renewable electricity production, both domestically and in its neighboring countries. Because of the importance of the hourly magnitudes of import and export of electricity, a soft link between OPERA and the European electricity market model COMPETES [32, 33] can be realized. This link has been established in the FLEXNET project [17]. The hourly net import profile was in this case treated as an additional electricity supply option. The hourly net export profile as an additional electricity demand option. Both additional options were not allowed to deviate from the imposed profile.

4.3 Output examples

To give an idea about the kind of analysis that can be realized using OPERA, an illustrative model run has been executed. As a baseline the National Energy Outlook of 2016 was taken [29]. The additional scenario that was projected with OPERA is derived from the Standard scenario as used by Ros and Daniëls [15] with the difference that for 2030 and 2050, respectively a CO_2 penalty of 50 and 400 €/tCO_2 was used instead of GHG targets. Furthermore, the model contains some extensions as compared to the version used by Ros and Daniëls [15]. The model version used in this article contains extreme mode options (section 3.5) and electro fuels [34].

Figure 3 presents electricity production for the baseline and scenario run. A decommissioning of all Dutch coal-fired power plants after 2029, as stated by the coalition Government that took office in 2017, is not included in the scenario run as it was not part of the National Energy Outlook 2016. Applying a CO_2 tax of 50 €/tCO_2 in 2030 implies on the one hand an increase in gas and wind generated electricity production, and on the other hand a decrease in electricity production from other sources. Also other sectors are affected by the CO_2 tax and shift to less carbon intensive alternatives to meet their demands. The net effect of this penalty is a modest increase in electricity production of 7 TWh. The CO_2 tax of 400 €/tCO_2 as applied to the 2050 case results in a strong electrification of energy services leading to a large increase of electricity production mainly from wind offshore technology. Fossil based generation is phased out to a large extent. Electricity production increases from 140 TWh in the baseline to 235 TWh in the CO_2 tax scenario in 2050.

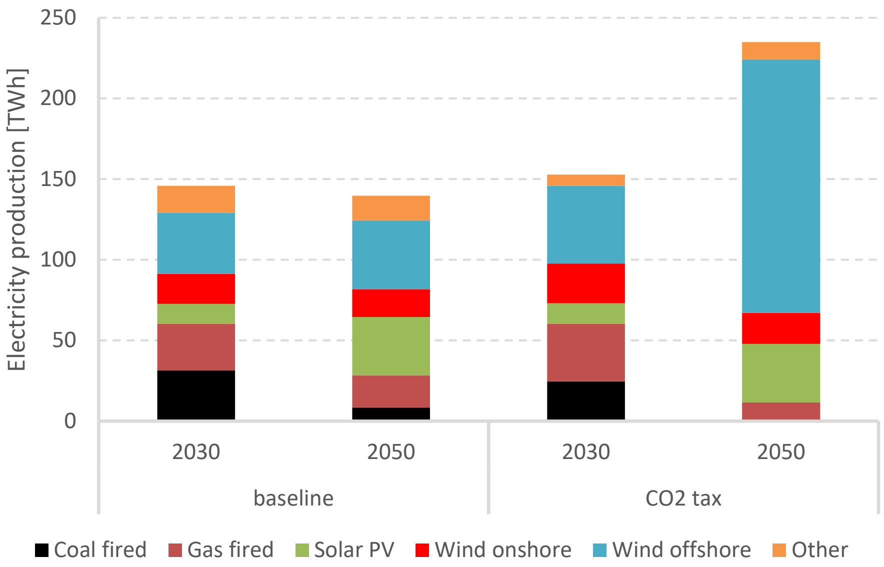

Figure 3 Electricity production [TWh] in 2030 and 2050 for the baseline and for a scenario with a CO_2 tax.

A CO_2 tax of 50 €/tCO_2 in 2030 has a significant effect on total GHG emissions as illustrated in Figure 4. In all sectors, except for industry and households, CO_2 emissions are 25% lower than in the baseline. In total the GHG emissions are reduced by 40% in comparison to the 1990 level of 221.4 MtCO_2eq. Applying a CO_2 tax of 400 €/tCO_2 in 2050 has large effects. The total level of GHG emissions drops to 21.1 MtCO_2eq, which corresponds to a reduction of approximately 90% in comparison to the 1990 level. Non-negligible emissions remain in transport and households, as well as from other greenhouse gases like methane and nitrous oxide. In industry net GHG emissions become negative. This can be attributed to the use of biomass in combination with CCS technology.

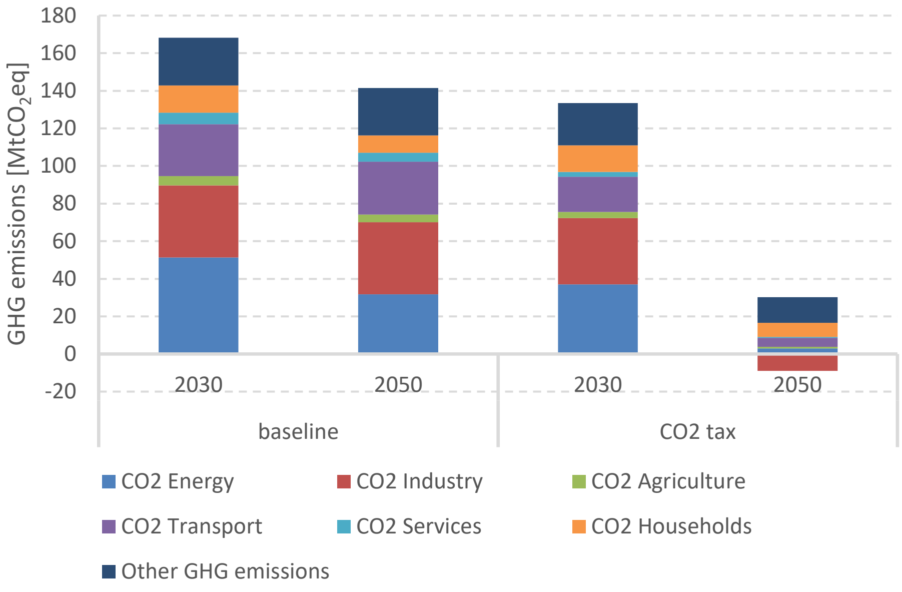

Figure 4 GHG emissions [MtCO_2eq] in 2030 and 2050 for the baseline and for a scenario with a CO_2 tax. Emissions are decomposed as CO_2 emissions per sector and other GHG emissions on a national level.

5 Conclusions and prospects

This article gives an overview of the main characteristics of OPERA, a new energy system optimization model for the Netherlands. The strengths of the model lie in its ability to cover the full energy system with a high time-resolution. The use of a high time-resolution makes it possible to accurately capture the variability of energy demand and supply in different periods. Electricity market models sometimes use an even higher time resolution, but have as major drawback that they lack information about the rest of the energy system and do not allow for balanced assessments of how to best accommodate large amounts of variable renewable energy supply. Because of OPERA's capability of addressing the intrinsic intermittency of renewables such as solar and wind energy, the model has proven to be a special asset for strategic advice and policy design for the Dutch government. The model contains a well-founded baseline, which constitutes a calibrated and broadly accepted reference point for analyses by which the effects of gradually more stringent GHG emission reduction ambitions can be investigated.

To further increase OPERA's relevance as tool for analyzing system integration topics, we foresee several possible improvements, some of which are currently being implemented. First, different temperature levels for industrial heat can be added, and the potential use of waste heat could be represented. This would make it possible to give a more accurate description of the possibilities with regard to the exchange of heat between different processes and sectors. Second, an important improvement could be the division of the building sector into separate segments based on e.g. current level of energy demand and insulation, type of construction, and whether it is possible to apply district heating. This would enable a more refined modelling of energy savings opportunities and the effect of demand response on energy profiles in the built environment. Third, the disaggregation of the Netherlands into distinct geographical regions would improve the simulation of, for instance, infrastructure costs, and of energy options possessing features that are determined at the local rather than national level. An option like geothermal energy, for example, would particularly benefit from such a geographical disaggregation (see [35]). Fourth, OPERA's extension into a fully-fledged dynamic model would allow for optimization over a specified time frame spanning multiple years or decades. This would make OPERA even more valuable for policy and strategic analysis than it is already today, because it could thereby teach us something about *when* to take certain measures and how the path towards a set target could look like. Finally, in the longer run we aim at geographically expanding or replicating OPERA so that its database also includes other EU countries. This would substantially extend the applicability of the model and allow for assessing energy and climate policy questions in their full European dimension.

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Appendix

The allocation of hours into time-slices relies on the idea that hours with a similar character can be grouped together, without significantly affecting the level of insight in the final results. In this context we use the word 'character' to designate all features of a certain hour in terms of energy supply and demand. Table A1 lists the features explicitly modelled in OPERA to define the character of a certain hour, along with a short description and an explanation for their relevance.

Table A1 Features used to characterize time-slices.

Feature	Description	Relevance
1. Season of the year	The season of the year in which the hour occurs (winter, spring, summer and autumn)	Reflects seasonal variations of demand and supply (e.g. demand for heating is higher during winter than in summer)
2. Day of the week	The day of the week in which the hour occurs (Monday through Sunday)	Reflects intra-week variations of demand levels (e.g. during weekends demand for energy is higher in the residential sector than in office buildings, and vice-versa during workdays)
3. Part of the day	The part of the day in which the hour occurs (morning, afternoon, evening or night)	Reflects intra-day variations of demand and supply (e.g. demand for lighting is higher in the evening and at night; there is no solar irradiation at night; peak electricity demand usually occurs in the evening)
4. Likelihood of excess supply (*peaks*)	Based on historic data, the model estimates the likelihood that energy supply from intermittent sources in the hour exceeds demand. Hours where this likelihood is high are referred to as *peaks*	Identifies the hours in which it is most likely that excess energy is produced and can be stored (e.g. very windy and sunny weather during low electricity demand hours)
5. Likelihood of insufficient supply (*valleys*)	Based on historical data, the model estimates the likelihood that energy supply from intermittent sources in the hour is insufficient to meet demand. Hours where this likelihood is high are referred to as *valleys*	Identifies the hours in which it is most likely that not enough energy is produced, and the need to use stored energy arise (e.g. evening electricity demand peak on a dark day with no wind)
6. Distance between peaks and valleys	Number of hours between a peak and the following valley	Reflects situations when storage options might be of relevance (e.g. peaks that are close to valleys)
7. Intermediate hours	Based on historic data, the model estimates the likelihood that energy supply from intermittent sources in the hour is close to the demand level	Identifies the hours in which it is most likely that supply and demand are in balance and energy storage is not needed
8. Extreme hours	Hours in which extreme situations arise (e.g. when wind speeds are highest, wind is (nearly) absent, solar irradiation is strongest)	Avoid that extreme situations, which might determine important system features (e.g. the maximum needed peak capacity) are averaged out

For features 1 through 3, the user is free to choose what subdivision to apply. For example, it is possible to group spring and autumn into one single *intermediate* season (feature 1), or to divide the 24 hours of a day into 12 day-hours and 12 night-hours without further subdivision (feature 3). Features 4 through 8 can be specified using offset parameters. For example, with reference to feature 4, the user can provide a threshold above which the hours should be characterized as peaks.

Within this framework the user is able to choose the desired number of time-slices and devise a suitable mix of features to characterize them. For example, it is possible to only choose features 1 and 3 from Table A1 and divide the hours statically into six time-slices:

a. Intermediate day
b. Intermediate night
c. Summer day
d. Summer night
e. Winter day
f. Winter night

Alternatively, the user can devise a more sophisticated algorithm to define the character of each time-slice by taking into account all features at the same time. An example of such an algorithm, also based on 6 time-slices, might be:

- Allocate all extreme hours (feature 8) to time-slice 1
- Single out all peaks (feature 4) and valleys (feature 5), and allocate the peaks that are close to a future valley (feature 6) into time-slice 2 and all other peaks to time-slice 3. Further allocate all the valleys that are close to a peak in the past (feature 6) to time-slice 4, and all other valleys to time-slice 5
- Put all the remaining hours into time-slice 6 (feature 7)

Note that in this case the time-slice allocation is *dynamic*, in the sense that it will change if the user provides a different set of temporal profiles for energy supply and demand in the model input. It is possible to further split the hours introducing other dimensions, such as any of features 1 through 3, and by defining different threshold levels for the other features. For instance, with reference to feature 4, one can split the likelihood of excess supply into three tiers, high, medium and low.

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