D2.2 – A description of improvements in the system optimisation models used in the TradeRES project

Deliverable number:	*D2.2*
Work Package:	*WP2 – Optimal electricity trading with ~100% RES:* *Generation of a reference power system, scenarios, and input market data*
Lead Beneficiary:	*TNO Netherlands Organization for Applied Scientific Research*

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 864276

Author(s) information (alphabetical)		
Name	**Organisation**	**Email**
Germán Morales-España	TNO	german.morales@tno.nl
Juha Kiviluoma	VTT	juha.kiviluoma@vtt.fi
Niina Helistö	VTT	niina.helisto@vtt.fi
Ricardo Hernandez-Serna	TNO	ricardo.hernandezserna@tno.nl

Acknowledgements/Contributions		
Name	**Organisation**	**Email**
n.a		

Document information			
Version	**Date**	**Dissemination Level**	**Description**
1.0	23.03.2022	Public	Report providing a description of improvements in the system optimization models used in the TradeRES project.

Review and approval		
Prepared by	**Reviewed by**	**Approved by**
Germán Morales-España (TNO), Juha Kiviluoma (VTT), Niina Helistö (VTT), Ricardo Hernandez-Serna (TNO)	Silke Johanndeiter (EnBW)	Ana Estanqueiro (LNEG)

Executive Summary

The overall objective of this deliverable is to give an overview of the optimization models used in the TradeRES project, i.e., Backbone and COMPETES, their modelling capabilities and recent improvements. Within TradeRES, suitable market designs for a ~100% renewable power system are tested, making it necessary to represent better different energy sectors, flexibility options, and to capture a sufficient level of operational detail, flexibility sources and needs, which leads to reasonable investments. Before TradeRES, the models already included some of the representations mentioned below to different degrees. Nonetheless, improvements were needed to make the models suitable to optimize a future power system with 100% renewables.

The featured models optimize different technologies' investments and operation decisions while considering energy trade between countries. This deliverable includes a review of the main features of the models and their flexibility modelling capabilities. The latter are divided into three groups: temporal, sectoral and spatial. Temporal flexibility options adjust the demand or supply over time or reduce their forecast uncertainty. Sectoral options support the power system by coupling the power sector to other sectors, the power grid to other grids, or electricity to other energy carriers. Lastly, spatial flexibility options cover the capabilities that connect electricity surplus areas to electricity deficit areas.

The investment planning parts of the models require an appropriate representation of the temporal and operational characteristics of the system. Several model representations were studied to demonstrate the impacts of varying the temporal and operational detail on model accuracy and computational effort. The results showed that operational and temporal details have strengths and shortcomings in different systems. Moreover, temporal and technical representations impact the value of flexibility from different sources.

The optimization models were further developed to better couple with the hydrogen and heat systems. As a result, apart from planning optimal power generation and transmission expansion of electricity interconnectors, the models can invest in Power-2-H_2, H_2-2-Power and hydrogen transmission. Moreover, introducing new constraints improved the electricity sector link with the heat sector, allowing the model to invest in different heating types. The models' demand response (DR) options were improved by using appropriate linear constraints suitable for large-scale power systems and integrated energy systems models. Also, the DR representations maintain a sufficient level of detail that captures their physical capabilities.

Backbone was further developed to include dedicated reserve products, i.e., static and dynamic inertia requirements with simultaneous fast frequency reserve contribution. Implementing these products answers a need for specific products required in a system with high penetrations of VRE. Furthermore, dynamic line rating modelling was incorporated in Backbone by including the capability to consider the availability of transmission lines in time series form. Finally, formulation was developed to represent the charging and discharging of storage, including reserves provision and losses.

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1. Introduction

The TradeRES project will develop and test suitable market designs for a ~100% renewable power system. Such designs need to provide efficient operational and investment incentives in the long term to a system with high penetration of variable renewable energy (VRE) sources, i.e., wind and solar generation. The future power system to be tested is distinguished by its increasing integration with other energy sectors, e.g., heat, hydrogen and transport, and the active role of flexible demand of households and the industry. Moreover, it is necessary to test the performance of the market designs in a system with realistic representations of the different sources of flexibility such as VRE, demand response (DR), reserve products, storage, and electricity transmission.

In this deliverable, we focus on the existing capabilities and improvements in the optimisation models, Backbone and COMPETES, that are required to address the challenges posed in the TradeRES project. The improved optimisation models will identify the 'optimal' system configurations from a total cost perspective. The optimal system(s) will provide the benchmark portfolio of VRE, controllable generation and other flexibility sources, and indicate a reference pricing structure that disregards market imperfections.

The deliverable is set out as follows. Section 2 provides an overview of the main features, assumptions and modelling capabilities of the two optimisation models used in the TradeRES project, i.e., Backbone and COMPETES.

Section 3 focuses on the modelling improvements of the optimisation models. The improvements described in this section are in the following areas:

- operational detail in the investment phase;
- the link between the power sector and other sectors;
- demand response;
- dedicated reserve products;
- modelling of energy storage and power lines including reserves;
- time-series availabilities and losses of transmission lines.

Finally, Section 4 contains the conclusions of this deliverable.

The outcomes of this deliverable relate directly to several work packages and tasks within the TradeRES project. The improved models described in this deliverable will use the set of scenarios developed in task 2.1 and the collected input data required for each case study. In task 2.3, the models will be used to provide the necessary benchmark scenarios to test the market designs proposed in WP3 under specific case studies described in tasks 5.3 and 5.4. Finally, the optimisation models can give insights on representing sectoral flexibility options to the agent-based models depicted in task 4.1.

2. Optimisation models in the TradeRES project: An Overview

The TradeRES project maintains, develops, and uses two optimization models: Backbone and COMPETES. Both models optimize investment and operation decisions for a set of technologies e.g., VRE and conventional generation. Moreover, they can optimize the use of flexibility sources while considering the trade of electricity between countries.

Section 2.1 and 2.2 give a short introduction to the optimization models highlighted in this report and it also provides further literature for the interested reader. Section 2.3 gives an insight on the main market assumptions used in these models. Finally, Section 2.4 outlines the main modelling capabilities of the models related to the representation of temporal, spatial and sectoral flexibility.

2.1 Backbone

Backbone (Helistö, Kiviluoma and Ikäheimo, et al. 2019) represents a highly adaptable energy systems modelling framework, which can be used to create models for studying the design and operation of energy systems, both from investment planning and scheduling perspectives. It includes a wide range of features and constraints, such as stochastic parameters, multiple reserve products, energy storage units, controlled and uncontrolled energy transfers, and, most significantly, multiple energy sectors. Both high-level large-scale systems and fully detailed smaller-scale systems can be appropriately modelled.

The framework has been implemented as the open-source Backbone modelling tool using General Algebraic Modelling System (GAMS) and it is available at https://gitlab.vtt.fi/backbone/backbone. The tool minimises the total investment and operating costs of the system. The formulation is based on mixed-integer programming (MIP) and takes into account unit commitment decisions for power plants and other energy conversion facilities.

The adaptability of Backbone extends to several dimensions: temporal, spatial, technology representation and market design. Stochastic inputs can be represented with short-term forecasts and longer-term statistical uncertainties. It is possible to vary time step durations, select representative periods, and define rolling optimisation structures. Due to the modifiable node-unit structure, multiple efficiency representation alternatives and aggregation possibilities, technologies can be modelled with appropriate accuracy. From the market design perspective, Backbone supports, for example, different reserve requirement and provision configurations as well as gate closures.

Backbone energy network structure consists of grids, nodes, and units. In addition, it is possible to define transfer links between nodes. Nodes represent connection points for these transfer links as well as units. Transfer links can only be defined between nodes in the same grid, while units can represent energy conversion between nodes in different grids. In addition, transfer links always connect to two nodes, while units can also connect to more than two nodes and in certain cases to just one node. Figure 1 shows an example of the energy network structure.

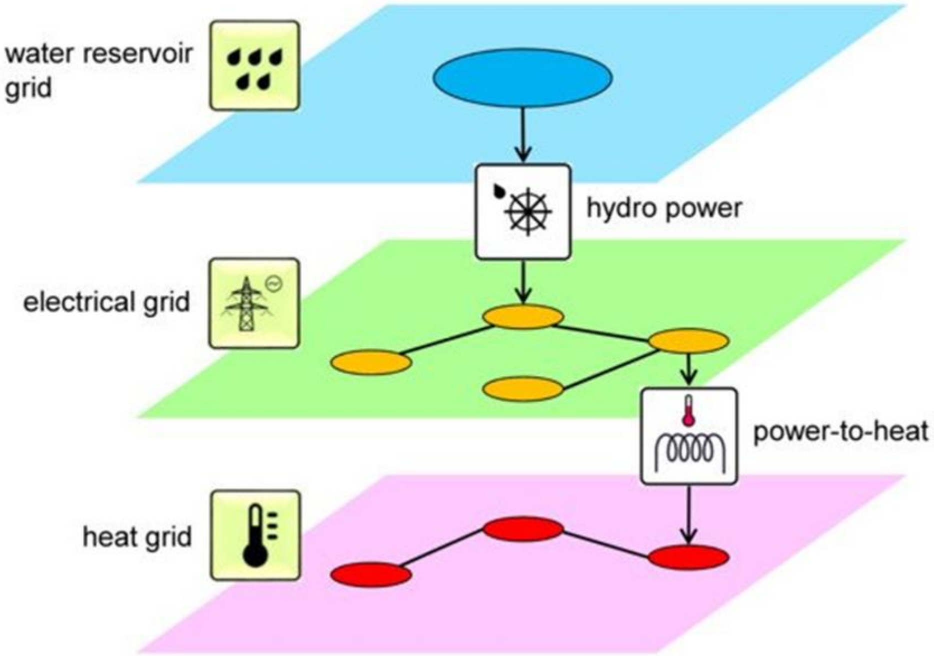

Figure 1 Example of the energy network structure in Backbone (Helistö, Kiviluoma and Ikäheimo, et al. 2019).

Backbone's temporal and stochastic structure consists of time steps, intervals, interval blocks, forecasts and samples. When giving time-series data, such as capacity factors of VRE or consumption of electric vehicles (EVs), the user also needs to define the duration of a single time step. The duration can be, for example, one hour or 5 minutes. When running Backbone, it is possible to aggregate these time steps by using interval blocks. For example, even if the underlying data was given at 5-minute resolution, the whole model can be run at 1-hour resolution by defining an interval block spanning the whole model horizon where the duration of the interval is 1 hour (12 time steps). Especially with rolling optimisation, it is often beneficial to define multiple interval blocks so that the immediate intervals have higher resolution and the intervals towards the end of the horizon have lower resolution.

Forecasts can be used to represent, for example, day-ahead forecasts. There can be one or more forecasts included in a forecast tree that branches from a selected interval. When using rolling optimisation, the model implements the first intervals and schedules future intervals. Then, the model horizon moves forward, the forecast tree is built again for the new situation, and the procedure continues.

Samples are another method to represent stochastic quantities in Backbone. They can be interpreted as representative periods selected from the timeseries. Samples can be combined as parallel alternatives or as sequential or circular timelines.

The objective function to be minimised in Backbone combines variable operational costs of units and transfer links, start-up and shutdown costs of units, ramping costs of units, fixed operational costs of units, investment costs of units and transfer links, changes in node state value, node state slack variable costs, and penalties from violating energy balance, reserve requirement and capacity margin constraints. Intervals, forecasts and samples are weighted according to their durations, probabilities and discount factors.

The main input data types are tabulated in Table 1 and the main output data types in Table 2.

Table 1 Main input data types of Backbone

Input group	**Main data types**
General system data	Capacity margins, resource limits, emission taxes and limits
Transmission data	Installed capacities, technical and cost parameters including coefficients for uncontrolled flows
Generation capacity and other technology data	Installed production and consumption capacities, storage capacities, technical and cost parameters
Time-series data	Energy demand, imports, hydro inflow, wind and solar generation, reserve requirements, fuel prices, node state boundaries
Fuel data	Emission rates

Table 2 Main output data types of Backbone

Output group	**Main output types**
Investments	Invested amount of each type of generation or other technology as well as transmission
Unit commitment and dispatch	Start-ups and shutdowns, online status, production or consumption, ramping, and reserve provision of each unit
Transmission between nodes	Use of transmission links
Emissions	Emissions from fuel consumption
Costs	OPEX: fuel costs, other fixed and variable operational and maintenance costs, emission costs, penalty costs from inflexibilities
	CAPEX: generation capacity and other technology investments, transmission link investments
Prices	Marginal cost of commodities (electricity, gas, heat, etc.)
Flexibility indicators	Loss of load, reserve shortages, spillage, VRE curtailment

2.2 COMPETES

COMPETES is a power system optimisation and economic dispatch model that seeks to meet European power demand at minimum social costs (maximising social welfare) within a set of techno-economic constraints – including policy targets/restrictions – of power generation units and transmission interconnections across European countries and regions.[1] The model is implemented in the Advanced Interactive Multidimensional Modelling System (AIMMS).

COMPETES consists of two major modules that can be used to perform hourly simulations for two types of purposes:

- A transmission and generation capacity expansion module to determine and analyse least-cost capacity expansion under perfect competition formulated as a linear program to optimise generation capacity additions in the system;

- A unit commitment and economic dispatch module to determine and analyse least-cost unit commitment (UC) and economic dispatch under perfect competition, formulated as a mixed-integer program considering flexibility and minimum load constraints and start-up costs of generation technologies.

The COMPETES model covers all EU Member States and some non-EU countries – i.e., Norway, Switzerland, the UK and the Balkan countries (grouped into a single Balkan region) – including a representation of the cross-border power transmission capacities interconnecting these European countries and regions (see Figure 2). The model runs on an hourly basis, i.e., it optimises the European power system over all 8760 hours per annum.

Over the past two decades, COMPETES has been used for many assignments and studies on the Dutch and European electricity markets. In addition, it is used and regularly updated as part of the energy modelling framework for the annual Climate and Energy Outlook of the Netherlands (NEV/KEV; see, for instance, PBL et al., 2019).

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[1] Over the past two decades, COMPETES was originally developed by ECN Policy Studies – with the support of Prof. B. Hobbs of the Johns Hopkins University in Baltimore (USA) – but since 2018 it is used/developed commonly by the Netherlands Environmental Assessment Agency (PBL) and TNO Energy Transition Studies.

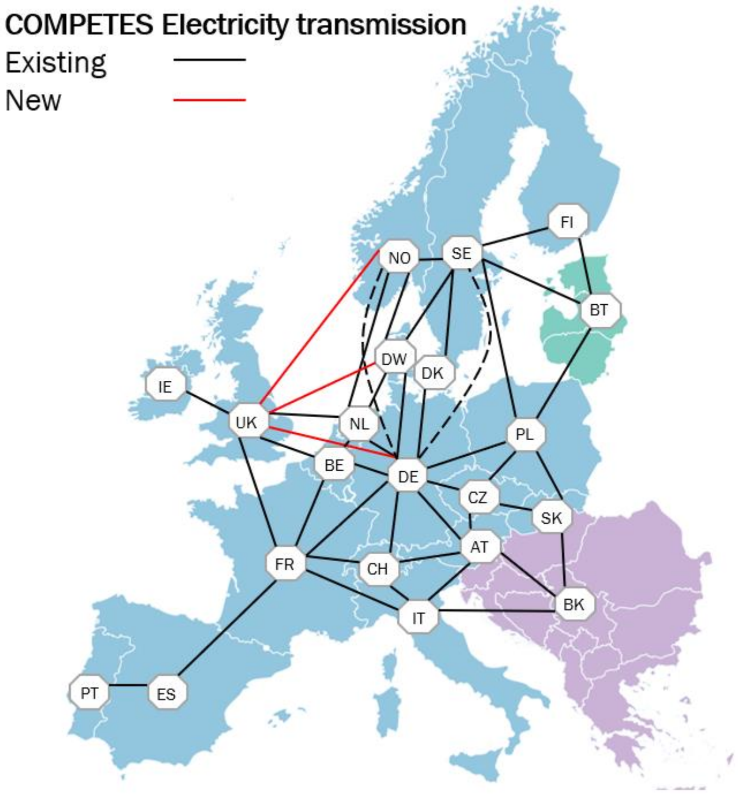

Figure 2: The geographical coverage of the COMPETES model

For each scenario year, the major inputs of COMPETES include the following:

- Electricity demand across all European countries/regions, including conventional power demand and additional demand due to further sectoral electrification of the energy system utilising P2X technologies;
- Power generation technologies, transmission interconnections and flexibility options, including their techno-economic characteristics;
- Hourly profiles of various electricity demand categories and renewable energy (RE) technologies (notably solar, wind and hydro), including the full load hours of these technologies;
- Assumed (policy-driven) installed capacities of RE power generation technologies;
- Expected future fuel and CO_2 prices;
- Policy targets/restrictions, such as meeting specific RE/Greenhouse gas (GHG) targets or forbidding the use of certain technologies (for instance, coal, nuclear or CCS).

As indicated above, COMPETES includes a variety of flexibility options:

- Flexible power generation:
  - Conventional: gas, coal, nuclear;
  - Renewable: curtailment of solar/wind;
- Cross-border power trade;
- Cross-border hydrogen trade;
- Storage:
  - Pumped hydro (EU level);
  - Compressed air (CAES/AA-CAES);
  - Batteries (EVs, Li-ion, PB, VRB);

    - Underground storage of hydrogen;
- Demand response:
    - Power-to-mobility (P2M): EVs, including grid-to-vehicle (G2V) and vehicle-to-grid (V2G);
    - Power-to-heat (P2H): industrial (hybrid) boilers and household (all-electric) heat pumps;
    - Power-to-gas (P2G), notably power-to-hydrogen ($P2H_2$);

On the other hand, for each scenario year and for each European country/region, the main outputs ('results') of COMPETES include:

- Investments and disinvestments ('decommissioning') in conventional and VRE power generation;
- Investments in interconnection capacities, both for electricity and hydrogen;
- Investments in storage;
- Hourly allocation ('dispatch') of installed power generation and interconnection capacities, resulting in the hourly and annual power generation mix – including related CO_2 emissions and power trade flows – for each European country/region;
- Demand and supply of flexibility options;
- Hourly electricity prices;
- Hydrogen prices;
- Annual power system costs for each European country/region.

For a more detailed description of the COMPETES model, see Appendix A in (Sijm, et al. 2017). See also (Ö. Özdemir, B. F. Hobbs, et al. 2019) and (Ö. Özdemir, B. F. Hobbs, et al. 2020).

2.3 Main market assumptions

The optimization models can simulate an equilibrium in an energy market. The market equilibrium is modelled by posing a profit maximization problem for each market party. Moreover, the supply, demand, and net import positions clear at each node of the network, which can represent a single physical node or zone (e.g., country or region) depending on the input data, resulting in nodal or zonal prices. The optimal decisions of each market party are aligned with their own interest, for example:

- The power generators decide on a generation output and the capacity investment required in conventional or renewable technologies to maximize annual profits. The revenues from the generator depend on the spot price of electricity at which the generator sells its power.
- Storage operators, such as hydro pump and batteries, aim to maximize their net revenues by injecting and withdrawing power to the grid. Storage consumes (buys) energy during hours with low electricity prices and produces (sells) energy during high priced hours. This behavior increases or decreases the electricity demand depending on the electricity prices, providing flexibility to the power system.
- Flexible demand, on the other hand, aims to minimize its consumption costs by shifting (or curtailing) load from (during) high electricity prices to low electricity prices.

- The transmission system operator (TSO) can be considered as a power pool operator who buys energy from generators and sells it to consumers. The objective of the TSO is to maximize the revenues obtained from congestion rents.

To model market equilibria, a complementarity problem can be defined by concatenating the first-order KKT conditions for each market party's problem, i.e., generators, storage, demand and TSO operators, with the market-clearing conditions. The resulting complementary problem is computationally very challenging and, in practice, is limited to small case studies. Although solving any particular market equilibrium for a large-scale system may not be computationally feasible, the problem becomes much easier to solve under the assumption of perfect competition, since the complementary equilibrium problem has a single equivalent optimization problem (Gabriel, et al. 2012).

In conclusion, under the assumption of perfect competition, the market equilibrium problem where each market party maximizes its profits, is equivalent to a single optimization problem where the social welfare is maximized (or system costs minimized) subject to 1) the combined set of first-order conditions (constraints) from all market parties, and 2) market clearing conditions (e.g., supply-demand energy and reserves balances). This single equivalent optimization problem also applies to optimal linear investment problems, as proved in (Ö. Özdemir, B. F. Hobbs, et al. 2019).

2.4 Modelling capabilities

In this section we summarize the temporal, spatial and sectoral flexibility options that are represented in COMPETES and Backbone.

Similarly as in the TradeRES WP4 deliverables (Couto, Schimeczek, et al. 2021), (Schimeczek, et al. 2021) and (Couto, Silva, et al. 2022), we use the terminology for flexibility as specified in Table 3.

Table 3. Flexibility definitions within TradeRES

Term	Explanation
Flexibility option	Asset or measure supporting the power system to balance electric demand and supply, and compensate for their stochastic fluctuations stemming from, e.g., weather or consumer behaviour…
Temporal flexibility option	… by adjusting demand and or supply as function over time or by reducing their forecast uncertainty;
Sectoral flexibility option	… by coupling the power sector to other sectors, the power grid to other grids, or electricity to other energy carriers;
Spatial flexibility option	… by connecting electricity surplus areas to electricity deficit areas.

2.4.1. Temporal flexibility

In Backbone and COMPETES, temporal flexibility options are represented in the day-ahead, intraday and reserves markets as described in Table 4. Both models have implemented options that can shift demand or supply over time, such as load shifting and storage technologies. In addition, Backbone has a better representation of short-term markets, different reserve products are included, and it can trade in different time units.

Table 4. Temporal flexibility options

Market design	**Backbone**	**COMPETES**
Shorter lead times between market closure and delivery	✓	
Rolling time-horizon market clearing process	✓	✓
Trade shorter time units, e.g., 30, 15 or 5 minutes	✓	
Balancing markets	✓	
FCR market	✓	
aFRR market	✓	
mFRR market	✓	
Real-time pricing	✓	
Load shedding	✓	✓
Load shifting	✓	✓
Storage Technologies (P2X2P)	✓	✓

2.4.2. Sectoral flexibility

As defined in Table 3, sectoral flexibility options support the balancing of the power system by coupling the power sector to other sectors and using their complementarities to contribute to the decarbonization of the energy sector. This sector coupling links different energy carriers – such as electricity, heat, and gas – and end-use sectors – built environment, transport, and industry. It is crucial to capture the interactions between sectors and assess their impact on the power system. Consequently, several improvements have been made to the optimization models to consider this cross-sectoral interaction when finding the optimal power system. Existing and new sectoral flexibility options are shown in Table 5.

Table 5. Sectoral flexibility options

Market design	**Backbone**	**COMPETES**
Interactions with heat sector	✓	✓
Interactions with transport sector	✓	✓
Interactions with industry processes	✓	✓
Spot market for H_2	✓	✓
H_2 network tariffs	✓	
Cross border H_2 trading	✓	✓
Design of short-term markets for electricity and hydrogen	✓	✓
Adjustment of network tariffs for electricity and hydrogen	✓	

2.4.3. Spatial flexibility

Sharing resources across borders takes advantage of the different generation portfolios, weather conditions and load patterns. An important benefit of integrating European electricity markets is the efficient use of renewable energy production; spatial flexibility can achieve emission and system cost reductions by allocating clean resources by cross-border trade. Several spatial flexibility options are modelled in the optimization models; these options are found in Table 6.

Table 6. Spatial flexibility options

Market design	Backbone	COMPETES
Redispatch within price zones		✓
Flow-based market coupling	✓	✓
Nodal pricing	✓	✓
Dynamic line rating	✓	
Cross border intra-day markets	✓	
Cross border reserve markets	✓	
Cross border capacity markets	✓	

2.4.4. Market and policy mechanisms

Besides the energy-only market, which compensates for the power produced, the optimization models can include different types of mechanisms that can ensure system adequacy, like capacity mechanisms. COMPETES has been coupled with the agent-based model EMLab to simulate a capacity market. Moreover, Backbone has a capacity margin requirement. Other policy mechanisms include market premia. Finally, a representation of the emissions trading system is implemented in Backbone.

Table 7. Market and policy mechanisms options

Market design	Backbone	COMPETES
Energy-only market	✓	✓
Capacity mechanisms	✓	✓
Market premia	✓	✓
ETS	✓	

3. Improvements in the optimisation models

In this section, we summarise the main enhancements in the optimisation models developed during the TradeRES project. These improvements are in the following areas: the temporal and operation detail in the investment phase, the integration with other energy sectors, demand response, dedicated reserve products, modelling of energy storage and power lines including reserves, and time series availabilities and losses of transmission lines.

3.1 Operational and temporal detail in the investment phase

Planning of future energy systems with higher prevalence of wind and solar energy requires a careful representation of the temporal and operational characteristics of the system in the investment planning model. A study carried out with Backbone in (Helistö, Kiviluoma and Morales-España, et al. 2021) identifies the aspects that should be considered when selecting the representation for a particular system. In order to demonstrate the impacts that various model representations have in terms of model accuracy and computational effort while highlighting the system-specific nature of the problem, Backbone was applied to two CO_2 price scenarios and to two test systems: a solar-dominated power system, and a wind-dominated power and district heating system. The temporal and operational representation of the model in Backbone's investment planning stage was varied and the operational costs of the planning outcome were further defined by running Backbone in the scheduling mode with full temporal and operational detail.

Different methods for time series reduction for the investment planning stage were compared and the consequences of different ways to model storage state evolution were demonstrated. More specifically, the evaluated methods included full year representation, representative week modelling with cyclic and continuous storage state assumptions, and a new aggregation strategy where a selected set of weeks is represented by a high resolution and the rest of the time horizon by a low resolution. It was shown that the proposed temporal sampling strategy can better capture the dynamics of the wind-dominated system with longer-term storage needs, while representative weeks were more suitable for the solar-dominated system with short-term storage.

On the operational detail side, the study considered unit commitment decisions, frequency containment reserve requirements, ramp limits with hourly and sub-hourly resolutions, as well as a new constraint to correctly represent the provision of very fast reserve products and rotational energy, important in future power systems with fewer online synchronous generators. In addition, the impact of modelling flexibility emerging from sector integration was examined with different levels of detail. As with the temporal representation comparison, the results showed that operational details have different benefits and weaknesses in different system types. Furthermore, the results showed that appropriate modelling is crucial for analysing the value of flexibility provided by different technologies.

Based on the findings, testing several temporal and technical representations for each particular system is recommended in order to ensure the feasibility of the selected method for that purpose

3.2 Integration with other energy sectors and demand response

This section addresses the modelling of the interconnection of the power system to other energy sectors such as transport, heat and industrial energy demand. Improvements in the optimization models are such that they can integrate different sectors by transforming affordable and sustainable electricity to serve different end-use sectors. The reader is referred to (Kiviluoma, Koreneff and Similä 2021) for a comprehensive review of the interactions between electricity and other energy sectors.

3.2.1. Hydrogen

Hydrogen has the great potential to bring green energy, typically from electric VRE production, to those sectors where direct electrification is technologically challenging or economically inefficient. Hydrogen is also a viable green alternative to replace other energy carriers in form of liquids or gasses. Furthermore, hydrogen can play an essential as a long-term energy storage option in a system with 100% renewable electricity. Due to the hydrogen relevance in the design of future energy systems, it is imperative that power system models are coupled to a possible hydrogen system model.

In the TradeRES project, we further develop our power system models to couple them to a hydrogen system. Therefore, apart from planning the optimal power generation and transmission expansion of the system, the system optimisation models, COMPETES and Backbone, can now also expand the coupling technologies, power-2-H_2 and H_2-2-power, and the gas network. By simultaneously optimising the different sectors, an optimal complementarity between the sectors is achieved, thus supplying the electric and hydrogen demand in the most economical way.

The main investment decisions for the hydrogen system are taken for different electrolyser technologies (power-2-H_2), hydrogen-fired power plants (H_2-2-Power), hydrogen underground storage in salt caverns, and hydrogen transmission between countries. For the case of hydrogen storage, the system can independently invest in charging (compression) capacity, discharging (decompression) capacity, and storage size, thus allowing for a better exploitation of the dynamics between the hydrogen and power systems. For the hydrogen transmission, the starting point before optimisation is the current gas infrastructure, where the model can either decide between two possible retrofits (Wang, et al. 2021) (60% or 80% of energy content compared with methane) or build new pipelines only for hydrogen.

3.2.2. Demand Response

Demand response is expected to play a major role in integrating large shares of VRE sources in power systems. For example, DR can increase or decrease consumption depending on the VRE availability, and use generating and network assets more efficiently. Detailed DR models are usually very complex, hence, unsuitable for large-scale energy models, where simplicity and linearity are key elements to keep a reasonable computational performance. In contrast, aggregated DR models are usually too simplistic, and as widely discussed in (O'Connell, Pinson, et al. 2014), (Zerrahn and Schill 2015) and (Morales-

España, Martínez-Gordón and Sijm 2021), these models are flawed and the conclusions reached may be misleading.

The main drawback of DR models is that they consider ideal shifting, ignoring saturation and immediate load recovery, which are the two key characteristics present in most flexible loads (Gils 2014). To illustrate the effect of these to characteristics, consider the case of thermostatic controlled loads:

- Saturation: if electricity prices are very low for prolonged periods of time, ideal DR models will dictate sustained very high (or maximum possible) consumption; however, the local (comfort) constraints will prevent the temperature from exceeding a maximum threshold by stopping consumption, thus limiting (saturating) the maximum sustained high consumption of the appliance.
- Immediate load recovery: Continuing with the example of thermostatic controlled loads, if electricity prices are high, consumption can be initially reduced, but the local (comfort) constraints prevent the temperature from falling below a given threshold, at this point the local control will recover the load immediately by forcing consumption to restart (O'Connell, Pinson, et al. 2016)

Therefore, to more realistically represent the physical capabilities of flexible loads, we include saturation and immediate load recovery in our DR models. In COMPETES, we use a collection of linear constraints proposed by (Morales-España, Martínez-Gordón and Sijm 2021), which are appropriate for large-scale power systems and integrated energy system models, and are sufficiently sophisticated to capture the key effects of DR in the energy system. The DR models also include a mixed-integer programming formulation for load shifting that guarantees immediate load recovery, and its linear relaxation better approximates the exact solution compared with previous models.

3.2.3. Heat

Modelling investments in different heating types requires that the demand related to each heating type is also appropriately scaled because the total heating demand of, for example, heat pumps depends on the number of buildings heated with heat pumps. Otherwise, there is a risk that the model uses the heating type with the lowest variable costs also to heat those locations which did not invest in such option. For example, when electricity price is low and the total building sector's heat load is relatively modest, the model may use heat pumps to heat all buildings, even if not all buildings invested in a heat pump. On the other hand, the total building sector heat load cannot be separated into heat pump part and, for example, gas heating part already in the input data, because the aim is to let the model optimise the amount of investments in each technology.

In order to model investments in different heating types, a new parameter and constraint were added to Backbone that make it possible to model so-called fixed flow units. This way, by giving normalized heat demand time series to these fixed flow units and constraining the investments to different heating types as well as their fixed flow counterparts appropriately, it is possible to let Backbone optimize the shares of different heating options. Figure 3 shows an example of a unit-node structure for such a model. The same method can also be applied to vehicle investments, for example. While this improvement gives more possibilities for energy system modelling and analysis, the starting point in TradeRES scenarios is pre-defined electrification rates in both the building heating and transport sectors.

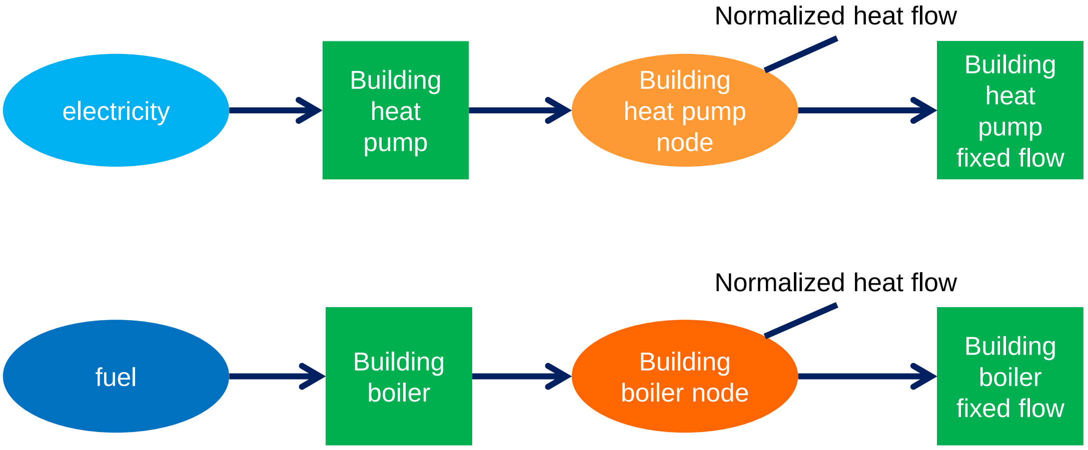

Figure 3 An example of nodes (ovals) and units (rectangles) to be defined for a model when optimizing investments in different heating types.

3.3 Dedicated reserve products

Backbone already had the capability to model online and offline reserve provision, constant and time series reserve requirements, reserve requirement based on the production of certain units, and N−1 reserve requirement. The default assumption is that units have to allocate separate capacity to different reserve products. However, it is also possible to let units allocate same capacity to multiple reserve products when the reserve products do not overlap.

Recently, Backbone was enhanced by adding static and dynamic inertia requirements with simultaneous fast-frequency reserve (FFR) contribution to the set of constraints (Helistö, Kiviluoma and Morales-España, et al. 2021). This means that it is possible to let units contribute to the inertia requirement not only according to their rotational energy but also by very fast reserve provision, due to an increasing prevalence of fast frequency products (Eriksson, Modig and Elkington 2018).

3.4 Tight linear programming modelling of energy storage and power lines including reserves

Storage systems for electricity have become a promising option to increase power system flexibility and accommodate larger shares of VRE. To get a full picture of the potential operation and benefits of storage systems, a realistic representation of their characteristics is essential in power system models. Storage technologies usually incur in dynamic losses when charging and discharging. Storage systems can also provide additional flexibility through reserve provision if they are able to change their charging and discharging level fast enough.

Existing storage models including dynamic losses require different variables to represent the charging and discharging processes, and also introduce binary variables to ensure that the storage cannot charge and discharge simultaneously, e.g., (Xu, et al. 2018). However, introducing binary variables requires to solve mixed-integer programs which can be computationally intractable in large-scale models, especially if the MIP formulation is weak. Therefore, energy models can greatly benefit from a tight MIP representation of energy storage because 1) it accelerates the solving times of MIP models, and 2) in its relaxed form, the linear programming (LP) solution will be very near to the optimal exact MIP solution. On the other hand, a weak relaxation can result in unrealistic and infeasible operation.

In the TradeRES project, we 1) develop an LP formulation of storage charging and discharging, including reserves provision and losses; 2) propose an MIP formulation that is the tightest possible, i.e., convex hull, thus its relaxed LP form minimises the possibility of simultaneous charging and discharging; and 3) the LP formulation is extended to include storage investment decisions.

Furthermore, the proposed LP formulation can be easily applied to transmission lines as well since they present a similar formulation. While storage systems shift energy in time, transmission lines shift energy in space. Transmission lines also have losses, they cannot have energy flows simultaneously in two directions, and the link can also be used to transfer reserve products between regions, see for example, Backbone in https://gitlab.vtt.fi/backbone/backbone.

3.5 Time series availabilities and losses of transmission lines

In order to enable dynamic line rating modelling, the capability to consider time series form availability of transmission lines was added to Backbone. The total capacity, including initial and invested capacity, is multiplied by the availability of the line, which can now be given in a constant or time series form, to get the available capacity for each time step.

In addition, the capability to model time series form efficiency of transmission lines was added to Backbone. The efficiency is taken into account both when transferring energy and when setting capacity aside to transfer reserve products.

4. Conclusions

Temporal and operational detail improvements

Various temporal and operational representations were studied to demonstrate their impact on the investment planning model, specifically its accuracy and computational effort. The Backbone model was applied to two CO_2 price scenarios and two different test systems, one characterized by high solar penetration and a wind-dominated system with district heating. The results showed that different temporal sampling strategies capture the dynamics of different systems better. The operational detail has different benefits and weaknesses in different system types like the temporal representation.

Sector coupling improvements

The integration of the electricity to other sectors was achieved by coupling the power system to the hydrogen system, a better representation of DR options and by improving the modelling of investments in different heating types.

The hydrogen system was integrated by modelling the investment in coupling technologies, power-2-H_2, H_2-2-power, hydrogen storage and retrofitting gas pipelines or investing in H_2 purposed pipelines. The optimal complementarity between the two systems is reached by achieving this integration, and the supply of electricity and hydrogen is done in the most economically efficient manner.

The demand response options in the models were improved to capture the physical capabilities of flexible loads better. On the one hand, detailed DR representations are complex, making them inadequate for large-scale energy models. On the other hand, aggregated DR models are frequently overly simplified, resulting in overoptimistic flexible capabilities. The proposed improvements achieve a better approximation compared with previous models, ensuring a more realistic representation of the physical capabilities of flexible loads while being suitable for large-scale power systems and integrated energy system models.

The heat sector was improved by adding a new parameter and constraint that allow the model to invest in different heating technologies. This enhancement guarantees that the investments in different technologies supply the location-specific heat demand.

Reserves, transmission lines and storage modelling improvements

Backbone was further improved by including dedicated reserve products, i.e., static and dynamic inertia requirements with simultaneous FFR contribution. As a result, generation units contribute to inertia requirements with their rotational energy and by very fast reserve provision. Furthermore, dynamic line rating modelling was incorporated in Backbone by including the capability to consider the availability of transmission lines in time series form.

Finally, an LP formulation was developed to represent the charging and discharging of storage, including reserves provision and losses. Also, the tightest MIP formulation was proposed. In its relaxed version, the LP solution is close to the optimal exact result of the MIP solution

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