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Energy models coupling: soft-Link between a long-term planning model and a dispatch model

EnergyScope TD - Dispa-SET

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Abstract

In this work we describe a bi-directional soft-link methodology between a long-term Energy System Optimisation Model (ESOM) and an Unit Commitment and Economic Dispatch (UCED) model: EnergyScope Typical Days (ESTD) [1] and Dispa-SET [2]. The soft-link is applied to the electrical and heating sectors.

The purpose of using this link is to gain insights into the adequacy and reliability of the output energy system given by ESTD. These are obtained via running Dispa-SET, as this has a greater technical and temporal resolution. When the energy system does not fit established adequacy criteria, a feedback loop is applied to the ESOM: new constraints are added to the model to improve the output system.

This link allows to get the best out of the two models rather than trying to incorporate all the features into one model, which could result in a long computational time. The method is automatic, and can be applied to complex energy systems, single or multi cell.

This methodology is applied to two cases: (i) an islanded Belgian energy system with a high share of renewable energy source and (ii) a scenario including both renewable and conventional energy production units (described in Limpens (2020) [3]). The results from the UCED model are complementary with the results of the ESOM regarding the unit dispatch. In fact, the soft-link method provides general trends regarding the way the ESOM outputs must be interpreted. Finally, in the two cases, the methodology ensured the energy system to meet the adequacy requirements.

Acknowledgements

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Contents

Acronyms

BEV Battery Electric Vehicle.

CAPEX Capital Expenditure.

CCGT Combined Cycle Gas Turbine.

CHP Combined Heat and Power.

COP Coefficient Of Performance.

DEC Decentralised.

DHN District Heating Network.

ENS Energy Not Supplied.

ESOM long-term Energy System Optimisation Model.

ESOMs long-term Energy System Optimisation Models.

ESTD EnergyScope Typical Days.

EUD End Use Demand.

GHG Greenhouse Gas.

GTUR Gas Turbine.

GWP Global Warming Potential.

HP Heat Pump.

HT High Temperature.

IND Industrial.

KPI Key Performance Indicator.

LoLE Loss of Load Expectancy.

LP Linear Programming.

LT Low Temperature.

MILP Mixed-Integer Linear Programming.

MTS Mid-Term Scheduling.

NTC Net Transfert Capacity.

OPEX Operating Expenditure.

P2G Power to Gas.

P2H Power to Heat.

P2M Power to Mobility.

PHS Pumped Hydro Storage.

PV Photovoltaic.

RES Renewable Energy Source.

SLF Synthetic Liquid Fuel.

TDs Typical Days.

THMS Thermal Storage.

TSO Transmission System Operator.

UCED Unit Commitment and Economic Dispatch.

1 Introduction

Climate change is a growing concern in the international scientific community. The impact of our society on the environment is growing with human activity, which results in increased Greenhouse Gas (GHG) emissions. As energy consumption is mainly responsible (though not solely) for these emissions, changing our energy system strategies (production, consumption and management) is necessary. The challenges are multiple: electrification of the heating and mobility sectors, implementation of Combined Heat and Power (CHP) units, and integration of renewable energy, etc. Dozens of new technologies are emerging to answer the challenges, and these interact across sectors (electricity, heat, mobility). Using all these emerging technologies, how can we build the cheapest reliable energy system which attains the climate objectives?

This is where long-term Energy System Optimisation Models (ESOMs) come into play. As mentioned in Collins (2017) [4], ESOMs are models mainly used to generate scenarios for the long-term evolution of energy systems. These generally incorporate many technologies, covering with the same level of detail the three main energy sectors: electricity, heat and mobility. Usually Linear Programming (LP) models, the ESOMs ensure the hourly production/consumption balance while minimising the total cost (investment and operation). The strength of such models is the possibility to create scenarios of energy transition while taking into account cross-sectoral interactions.

ESOMs also have their weaknesses: in order to reduce computational time, they have a low spatial, technical and temporal resolution. These low resolutions might under- or over-estimate the different capacities of technology to be installed in the considered scenario. About the spatial resolution, ESOMs are usually applied on one node (or cell). This node could be a region, country or continent. Therefore, ESOMs fail to represent relations within the node or interactions outside of it (e.g. the potential benefit of international cooperation for the integration of Renewable Energy Source (RES)) [4]. Concerning the issue of temporal resolution, these models consider typical time-slices to represent operational conditions of a whole year. Consequently, another weakness of the model is that operational constraints are often not considered. Bearing in mind that RES goes hand in hand with high temporal variability and high uncertainty levels, the consequent low temporal resolution will lead to under- or over-estimations of power capacity to be installed to meet the planned environmental objectives. Two methods have been proposed in the literature to tackle this problem.

Firstly, according to Collins et al. [4], one possibility to improve the ESOMs' temporal representation is to use a direct integration methodology. This results in an improvement in the temporal resolution of the ESOM, and the solution comes closer to the global optimum. For instance, this can be implemented using algorithms selecting specific time-slices or by modelling uncertainties through stochastic programming[1]. However, although these approaches would probably enhance the results, none of them are sufficient to guarantee a reliable system. Furthermore, these significantly increase the computational time.

The second suggestion is to soft-link the ESOM with another model. The present work is based on this idea. Concretely, the ESOM output energy system is used as input to

[1]All these methods are explained in details in [4]

the second model. The purpose of this additional model is to assess the adequacy and reliability of the energy system. The second model consequently needs to have higher technical and temporal resolution. This proves particularly useful for scenarios which contain a large share of renewables in the energy mix. These having high variability of production through a year, they are best represented with higher temporal resolution.

Eventually, this soft-link can be implemented in a uni- or bi-directional way. The latter possibility implies that new constraints are applied to the ESOM model, based on the outputs of the second model.

To efficiently soft-link an ESOM model, Unit Commitment and Economic Dispatch (UCED) models are the most appropriate. Those models analyse the operations of a given power system by only focusing on the Operating Expenditure (OPEX) [4]. This means it determines for every time step which units have to be committed in order to minimise the cost of supplying a given demand. Usually Linear Programming (LP) or Mixed-Integer Linear Programming (MILP) models, they are very precise regarding technical constraints such as ramping rates, start-up costs, minimum operating levels, etc. In addition, their time horizon is split into time steps of higher resolution (typically from 5 min up to one hour). The latter allows to take into account the high variability of RES as well as different constraints on ramping or frequency reserve. Finally, the last important feature of UCED models is that their scope is usually restricted to electricity sector. Therefore, cross-sectoral interactions (with the heating and mobility sectors) have to be taken into account in the soft-link.

Soft-linking ESOMs and UCED models should combine both models strengths (see Figure 1). The ESOM can make a first hourly energy balance based on typical time slices, leading to a scenario for a possible future energy system. This results in approximations in terms of (a) the installed capacity of each considered technology, (b) the primary energy consumption and (c) the total $CO_2 - eq$ emissions. Then the UCED model is able to (i) check the adequacy of the system with higher technical and temporal resolution and (ii) refine the ESOM results.

In this thesis, we present a soft-link methodology between the EnergyScope Typical Days (ESTD) [1][2] ESOM and the Dispa-SET [2][3] UCED model. The method is bi-directional since it includes a feedback loop on the ESOM, ensuring that a robust energy system is outputted. The main strengths of the methodology presented are: (i) the soft-link is automatic, relies on a methodology which is not case-dependent, (ii) the heat and electricity sectors are thoroughly handled and (iii) uni- or multi-cell systems can be investigated.

[2]Github with EnergyScope TD verions used in this work: [5]
[3]Github with Dispa-SET version used in this work: [6]

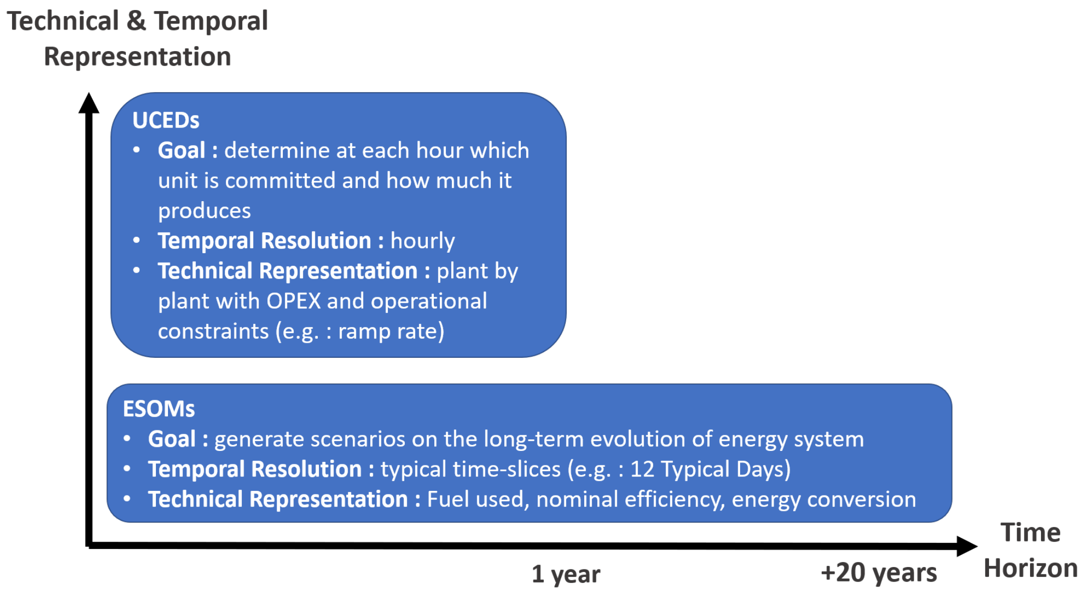

Figure 1: Comparison of the level of detail of ESOMs and UCED models. This representation outlines the advantage of a soft-link: representing a future energy systems with both high technical and temporal resolution, with low computational time.

In the following sections of this work, we present the two models. Then, an in-depth description of the soft-link methodology is proposed (including the concept, data processing, feedback loop and limitations). Finally, two case studies illustrating the methodology are presented: (i) an islanded Belgian system with high RES share and (ii) a mixed Belgian energy system composed of both RES and conventional technologies. Finally, the interested reader should note that a user manual has been written (Appendix E), and that the tools to use this soft-link are available on GitHub [7].

2 Methodology

This work presents a soft-link between the EnergyScope Typical Days (ESTD) and Dispa-SET models. Before going into the details of this methodology, this section first describes the two models. Some model adaptations have been implemented and are briefly covered in the second part of this section. Then the soft-link methodology is described. The latter takes place in two steps. The first one consists in processing inputs and outputs from the ESTD model to feed it in the Dispa-SET model. The adequacy of the power system is assessed via the results of Dispa-SET. If the adequacy requirements are not complied with, the second step takes place: this consists in modifying the ESTD optimisation, by adding new constraints in the model. The whole methodology is described in the next sections.

2.1 Models description

In this part, we give an overview of the ESOM model (EnergyScope TD) and UCED model (Dispa-SET). It involves the definition of the parameters and the key outputs of the models. In addition, the scope and limitations of the models are detailed.

2.1.1 EnergyScope TD

Context:

EnergyScope TD (ESTD) is an open-source Linear Programming (LP) model. It optimises both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) in order to provide an energy system able to meet yearly demand. Although the model presents an hourly time resolution, it does not optimise all 8760 hours in a year. It will pick a given number of time-slices to represent the whole year. These time slices are called Typical Days (TDs). They are selected to minimise the errors between the approximated and real duration curves of input data such as the End Use Demand (EUD) and the availability factors of renewable technologies[4]. An example is depicted in Figure 2 for Photovoltaic (PV) production. The reason for using TDs is to reduce the computational time [1].

Additionally, other constraints can be added to the problem. For example, a limit over the CO_2 emissions of the system, or the share of renewables among the primary energy resources.

This model represents the three sectors of energy consumption (electricity, heat and mobility) with the same level of detail. On top of that, it implements dozens of energy vectors and resources, and also more than 70 technologies. These features allow cross-sectoral interactions. This is specifically of interest when modelling future energy systems where interactions between sectors might grow (e.g. the production of Synthetic Liquid Fuel (SLF) using excess energy from renewables. The former can either be burned to produce heat or used for mobility purposes).

[4] the availability factor, for one specific moment, is the ratio between the maximum possible production of one unit and its installed capacity

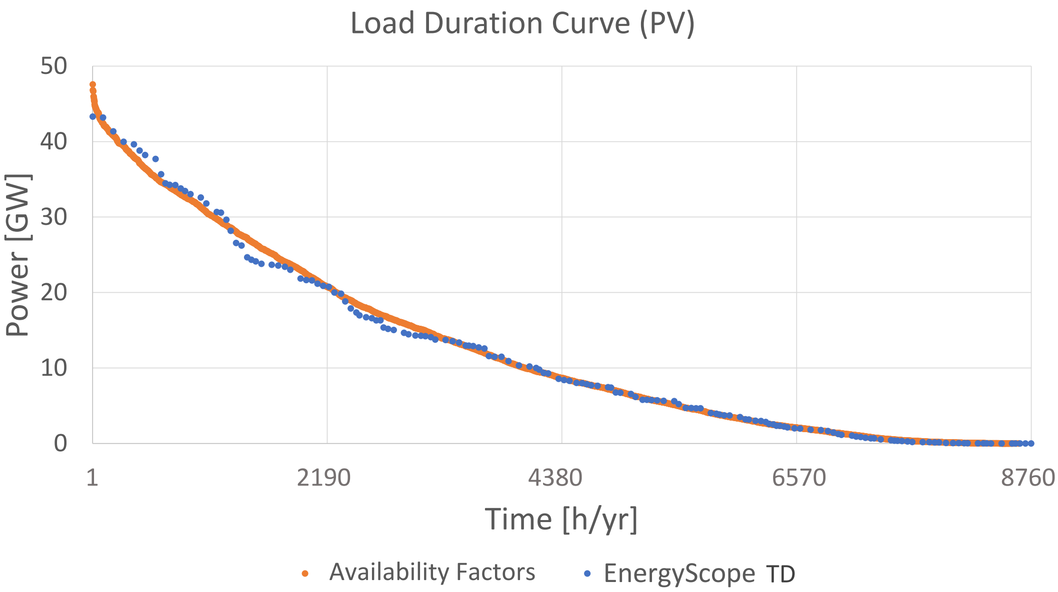

Figure 2: In EnergyScope Typical Days (ESTD), the Typical Days (TDs) are optimised to give a good approximation of the duration curve. Here as an example, the duration curve of the PV panel production in EnergyScope TD and the maximum possible production based on availability factors.

The working principle of the model is illustrated in Figure 3. Energy flows usually from primary energy resources on the left to the EUD on the right. In the middle of the figure, one can see the interaction between technologies and layers. 'Layers' represent all the elements which need to be balanced in each hourly time period [8]. As an example, electricity needs to be balanced at each moment between production, demand, imports and storage. Technologies allow conversion of quantities between layers. Note that there are three different heat layers: two Low Temperature (LT): Decentralised (DEC), District Heating Network (DHN) and one High Temperature (HT): Industrial (IND). This differentiation will be of importance in this work.

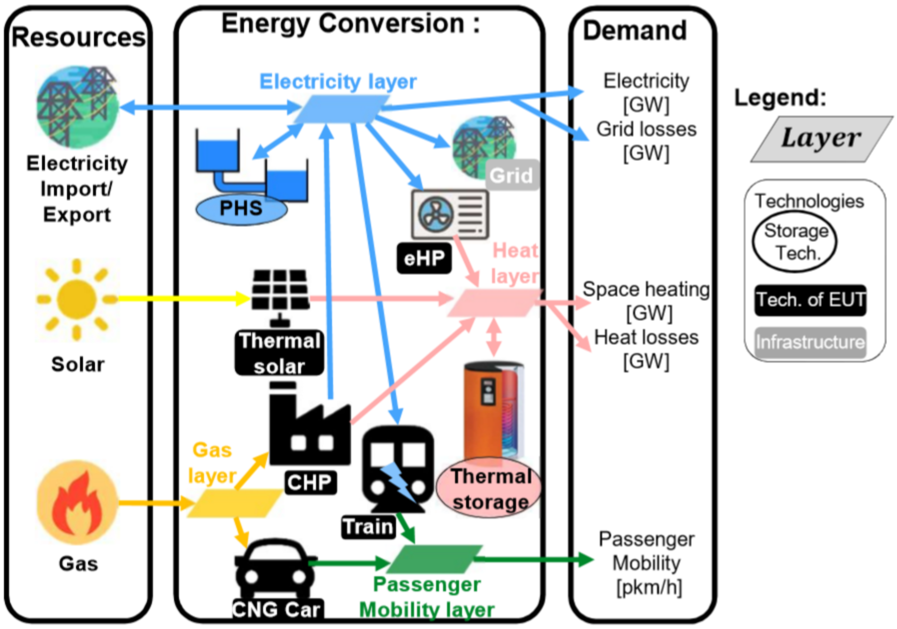

Figure 3: Representation of an energy system [1]. 4 layers are represented here (Electricity, Heat, Pasenger Mobility and Gas) and 7 technologies allow conversion of quantities between layers.

Inputs:

Several inputs need to be specified in order to perform the optimisation of the system. First of all comes the energy demand. This is specified at each hourly time period as an EUD for the three sectors: electricity, heating and mobility. Different parameters, which are specified by the user, can influence the way these demands are handled. As an example, one can specify the maximum share of the heat which can be handled through District Heating Network (DHN). Then comes all inputs which concern the supply. Most of these inputs are case dependent such as the availability of resources, or the cost of resources. The renewable availability factors as well as technology potential depend on the geographical area under study (e.g. the PV potential will not be the same in Belgium or in Spain). For further details, a full description of the EnergyScope TD inputs is available in Appendix A.1.

Outputs:

The main objective of this model is to define an energy system which respects the user-specified constraints, with either the lowest costs or lowest Global Warming Potential (GWP). The model will then give clear insight on (i) consumption of primary energy resources, (ii) $CO_2 - eq$ emissions per year, (iii) total costs (CAPEX and OPEX) and (iv) installed capacity of the different technologies.

The model also provides data regarding the balancing (i.e.: equality between production, imports or exports, demand and storage) of each layer, at each time step and for every TD. More details regarding EnergyScope TD outputs can be found in Appendix A.2.

Single cell:

The ESTD version used for this work [9] considers a single cell in its optimisation. This implies that interaction with the outside of the cell is represented only through exports and/or imports of electricity.

Limitations:

As stated earlier, ESTD optimises the system for a given number of Typical Days (TDs). These are time-slices selected to best represent the year under study with a limited number of days. This method reduces computational time but also introduces approximation errors into the results.

In addition, another weakness of EnergyScope TD (as for every ESOM) is that it is limited to technology characteristics such as efficiency, storage (dis)charge time, etc. The model does not consider operational aspects of the installed technologies (e.g. shut down of an electrical power plant, frequency reserve issues, etc). This can lead to approximate results versus the practical operation of the energy system.

Currently this model minimises its objective function by considering one cell at a time. This objective function comprehends either the costs (CAPEX and OPEX) or the GWP of the system (yearly $CO2 - eq$ emissions). It can however represent interactions with the exterior of the system through electricity imports and exports (with a fixed price). For these, ESTD considers a single interconnection line with the exterior (e.g. in the case of Belgium, one line of 5.8GW instead of several smaller ones). This implementation is too simple and does not represent correctly the reality, where congestion could occur. Such interactions need to be modelled properly since they will be crucial in future energy systems.

The previous limitations of the model (time resolution based on TDs, and technical resolution based on technology feature) justify the necessity of a soft-link with an UCED model, to ensure realistic and relevant simulation results.

2.1.2 Dispa-SET

Context:

The Dispa-SET model is a Unit Commitment and Economic Dispatch (UCED) focused on the balancing and flexibility problems in electrical grids, as explained extensively in [2]. In brief, with a given energy system as input, the model operates its economical dispatch so that the demand is met at every time step.

The optimisation is based on the OPEX. Several optimisation methods are available (e.g. Linear Programming (LP), Mixed-Integer Linear programming (MILP)) to minimise the objective function. The different methods are selected depending on the problem's complexity and level of accuracy required. The model includes continuous variables, which represent for instance the individual unit dispatched power or the curtailed power generation, and binary variables such as the commitment status (on or off) of each unit. Eventually, in contrast to the previous model, Dispa-SET can run with multiple cells.

The main advantage of this model is the way in which it treats the technical aspects of energy producing units. This means operational constraints are taken into account while optimising the system. However, one approximation of the model is that within each studied node, the grid is considered as an ideal conductor thus avoiding congestion issues, defaults or losses. In reality, congestion is possible within a zone (e.g. a country).

As a UCED model, the temporal resolution is higher than an ESOM. The latter uses a given number of time-slices and the former represents the system on an hourly basis for any given period. Among others, this has an impact on the representation of RES production. In Figure 4, is depicted an example where renewable energy production is discontinuous and over-estimated in EnergyScope TD.

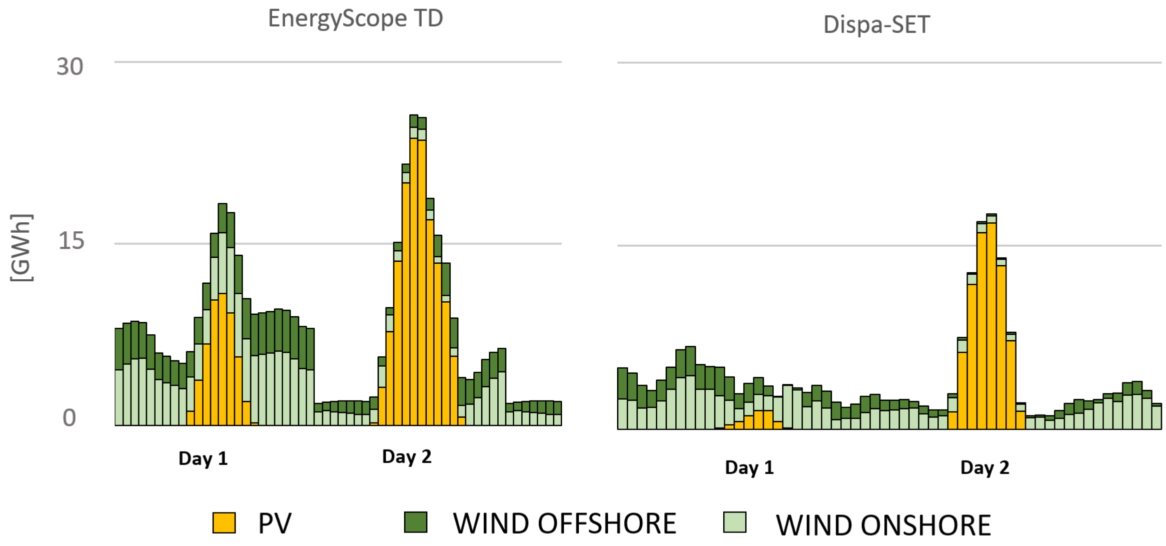

Figure 4: Representation of the electricity layer in EnergyScope and Dispa-SET for the two same days. In this example, the TD representation in EnergyScope over-estimates the RES production.

It is important to note that the model temporal resolution goes even further than the hourly scale as it considers the requirements of secondary and tertiary reserves. These need shorter time periods, than the time step of one hour, to be considered. The model uses additional constraints and equations to take these into account, thereby improving its temporal resolution.

Regarding spatial resolution, the model works by defining one or several linked zones. Within each zone (e.g. each country), all generation units need to be defined. Spatial resolution thus depends on the formulation of the problem.

As said earlier, the focus of Dispa-SET is on the electrical sector but heat, Power to Gas (P2G) and mobility can also be taken into account. The reader should note that heat is managed in a different way than in EnergyScope TD (See Figure 6, and section 2.2).

Inputs:

For each node studied, the main inputs needed to run the program are (i) a list of the electricity generating units and their features, (ii) the availability factors for each renewable energy source implemented and (iii) the electrical end-use demand. The input *Powerplant* database (see Appendix A.3) contains information regarding the technology features (efficiency) and operational characteristics (ramping power, no load costs, part load costs, storage losses, etc.). The availability factors and EUDs should be specified at every hourly time step. These series of values, given at successive times with equal hourly intervals, will be referred to as time series. Note that the *Powerplant* database can also be populated with Power to Heat (P2H) units, P2G and Combined Heat and Power (CHP) units. This helps to model cross-sectoral interactions.

In addition, Dispa-SET has the possibility to shed loads during the dispatch optimisation. This corresponds to a demand response. A price is associated to the amount of shedded load [€/MWh], so the model can reduce the EUD if it is economically advantageous. Next to that, Dispa-SET also models the loss of loads. These correspond to a failure in the optimisation when the demand can not be supplied. An exorbitant price is set for lost loads. The values of these two prices will have an impact on the economic dispatch.

For further analysis of a system, it is possible for the user to specify time series for the electrical lines Net Transfert Capacity (NTC), the cross border flows between zones, fuel prices, and other information. Exhaustive lists of Dispa-SET inputs can be found in Appendix A.3.

Outputs:

Once the model has been run, the user gets information on data such as primary energy consumption in each zone, state of charge of storage units, power generation per unit, CO_2 emissions per unit, etc.

Moreover, as stated earlier, the model focuses on balancing and flexibility issues. Hence, it can also give specific insights regarding the total energy curtailed. This corresponds to the forced reduction of energy output from renewable sources. As an example, curtailment can be caused by a lack of storage capacity. One can also gain insights on the system operation through a unit commitment plot, indicating which units are running at which time step, and hence analyse the number of times each plant starts up, etc.

Finally, the model provides insights regarding the adequacy of the electrical system under study. This is of importance as it is the focus of this work: to assess the adequacy of a given energy system. Typical indicators of adequacy are related to lost loads, load shedding, capacity reserve margin, etc. These are described in section 2.3.1. The reader should note that the adequacy in this work refers to balance between energy production and consumption, as well as tertiary frequency reserve. In other words, defaults or losses in the power system are not investigated.

Optimization length and Mid-Term Scheduling (MTS) [2]:

A country may have more than 300 power plants. Running the model with such a system would lead to long computation time. For this reason, the model considers smaller time steps to solve the problem. These smaller time steps are referred to as optimisation periods. These are typically 1 to 4 days and are run iteratively through the whole period of study. The initial values for Day j, are the last values of Day $j-1$. In order to ensure continuity (e.g. for storage levels), two optimisation periods need to overlap. The length of the overlap is defined as a look-ahead period. The latter is always smaller than the optimisation period.

To illustrate this, an example is shown in Figure 5 for an optimisation period of 2 days, and a look-ahead period of 1 day. The model considers a rolling time period of 2 days. So for the Day $j-1$, the optimisation will take place on Day $j-1$ and Day j. Results are kept for the Day $j-1$. Then the problem is solved for Day j and Day $j+1$ at the same time, and results are kept of the Day j. And so on, until the end of the optimisation period.

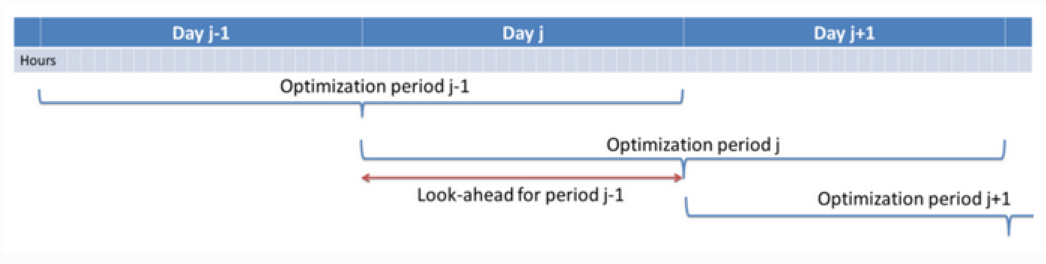

Figure 5: Representation of the smaller optimisation problems: slicing the time horizon of the problem in smaller time steps reduces greatly the computational time. In this example, the optimisation period is of 2 days with a look-ahead of 1 day [2].

This way of slicing the problem into smaller time periods has the great advantage of reducing computational time, but this is inadequate for modelling energy systems containing storage technologies. Some of these technologies, such as hydro dams, need a time horizon of a whole year in order to absorb seasonal variations of production and needs. With an optimisation period of a few days, such optimisation is impossible. Two solutions to this problem are possible.

Firstly, one can specify the storage charging level hour per hour as a time series based on historical data. Gathering this data is often difficult. The lack of such data can hinder accurate representation of scenarios with high renewable penetration. A second option is to use one of the Dispa-SET features called Mid-Term Scheduling (MTS). As specified in the model documentation [2], this is a simplified version of the Mixed Integer Linear Programming and power dispatch model. In other words, using MTS simplifies the modelling of the problem to take into account seasonal variations of production and demand. This allows forecasting and allocation of storage resources for the given period (not only for the optimisation period) with short computation time.

Heat management:

Regarding heat, Dispa-SET specifies one time series for each heat generating unit (i.e.: Combined Heat and Power (CHP) and Power to Heat (P2H)). This corresponds to the heat EUD associated with this unit. These units are always coupled to a storage unit. The storage capacity is considered to be zero if not specified otherwise. The time series EUD can also be met by an alternative heat supply (*HeatSlack* in Figure 6). There is a specific price associated with the *HeatSlack*. Hence, the model can then pick between the unit or the *HeatSlack* minimising OPEX.

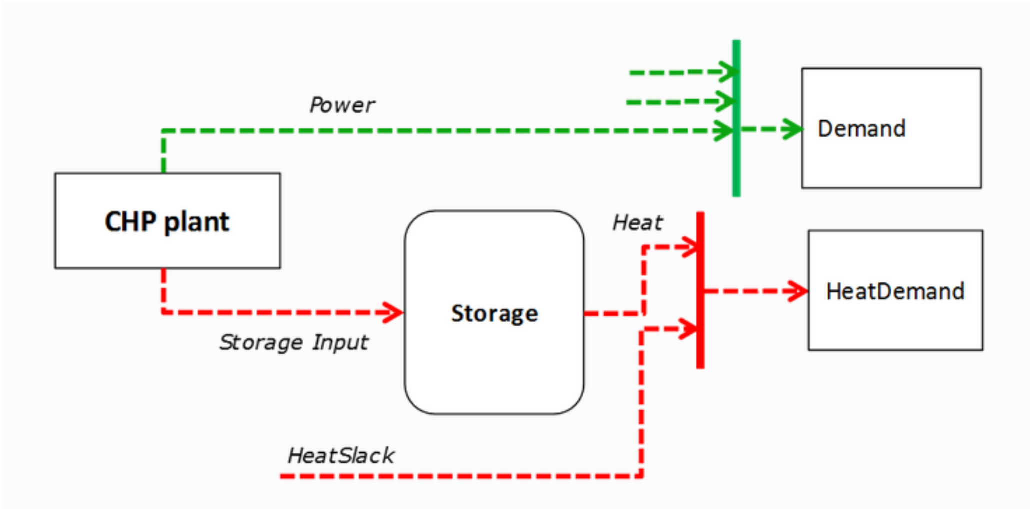

Figure 6: Schematic representation of the Heat Management in Dispa-SET for a CHP unit [2]. Hourly values of heat demand are specified for each unit individually. If the said unit can not supply the heat demand, the *HeatSlack* takes over.

The reader should note that in terms of heat production, EnergyScope TD can incorporate CHP, P2H units and other units. These other units are mainly boilers running on fuels, as well as heat generation units supplied by solar and geothermal energy. All of the latter will be aggregated into one *HeatSlack* in Dispa-SET.

2.2 Adaptation of the models

To ensure a coherent coupling between ESTD and Dispa-SET, two adaptations of the models have been implemented. Those two modifications are mainly linked to the heat management in Dispa-SET. The concepts are described in this section. Note that the modifications result in the *NewZones* version of Dispa-SET, available on GitHub [6].

2.2.1 New heat management in Dispa-SET

As stated earlier, not only do the two models differ in technical and temporal resolutions, but the heat management is also different (see Figure 6 for Dispa-SET). In order for the soft-link to give consistent output for different heat demand, we could:

- Keep the models as they are. This will induce intensive data processing between the two models.

- Change one of the two models, so that they would manage heat in comparable ways

The first option presents a problem: approximation errors will be introduced during the treatment of data. Whereas the second option will limit the processing needed, and thereby reduce the information loss. This is why we implement a different way of managing heat in Dispa-SET

The idea is simple: we use the same optimisation model for the heat as used for the electricity. This means that instead of specifying a heat demand for each unit separately, a single heat demand is specified and all the heat generating units are dispatched by the model to fulfill this demand. However, to simplify the modification, the thermal storage implementation remains the same. Therefore, every heat generating unit has its own thermal storage, independent from one another. This is represented in Figure 7.

To understand how the new heat management is implemented, let's first focus on the way the electricity sector is represented in Dispa-SET. The implementation is based on a **SET n**, which contains one or several zones (e.g. countries, called 'electrical zones'). Every zone considered is then part of **n** (e.g. **n** = {BE, FR}). To each 'electrical zone' are assigned multiple power production units, one end-use demand, etc.

So, in the same idea, a new **SET n_th** is introduced. This is the core of the new heat management. For each 'electrical zone', three 'heat zones' appear in **n_th**, one for each heat layer: DEC, DHN and IND (e.g. **n_th** = {BE_DEC, BE_DHN, BE_IND, FR_DEC, ...}). Similarly to the electricity related units, every heat production unit is linked to one element of **n_th**. On top of that, an input heat demand time series is required for each 'heat zone'. Finally, every 'electrical zone' is linked to three 'heat zones'. This allows interactions between the electricity and heat technologies of each zone (e.g. Power to Heat (P2H), Combined Heat and Power (CHP)) This concept is illustrated in Figure 7 for a single zone case. Note that the focus of this figure is on the heat sector management, therefore not all the electrical details are depicted.

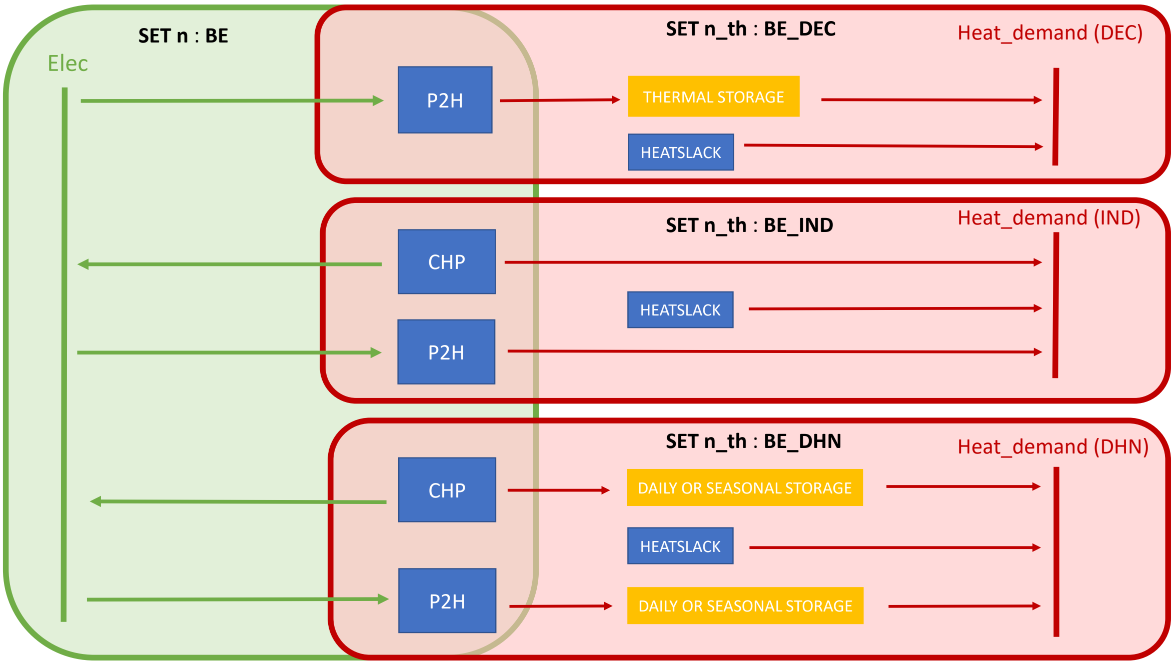

Figure 7: Schematic representation of the new heat management implemented in Dispa-SET. All CHP/P2H Units are defined within an 'electrical' and 'heat zone'. Every 'electrical zone' is linked to three 'heat zones'. Each 'heat zone' corresponds to one heat layer in EnergyScope TD. As an example, in this figure, for zone BE: we have **n** = BE, **n_th** = {BE_DEC, BE_DHN and BE_IND}. The CHP/P2H units interact with the electricity production/demand of the 'electrical zone' and their respective heat production/demand of the 'heat zone'.

2.2.2 New *HeatSlack* management in Dispa-SET

The initial *HeatSlack* implementation in Dispa-SET may lead to incoherent output data in regard to the ESTD constraints. As an example, in EnergyScope TD, resources can have a limit on availability (e.g. wood availability limited to 9 TWh per year). Hence, a boiler running on wood, being considered as *HeatSlack* in Dispa-SET, needs to have an upper production limit, reflecting the availability of wood. This is not the case in the version of Dispa-SET used in this work. So, in this section, the modifications added to the model to improve that element are briefly described.

The main issue linked to the *HeatSlack* is that one single price is assigned for the *HeatSlack* in the three heat layers (IND, DEC, DHN). To illustrate this problem, let's consider an energy system where boilers are installed only to produce IND heat. When processing data between one model and the other, no *HeatSlack* should be present in the DHN or DEC heat layers. In Dispa-SET, if the price of that IND *HeatSlack* is low, it will be competitive against other sources of heat in all layers. In other words, due to the low price, the model will get the chance to use a *HeatSlack* for the three heat layers. This is unrealistic since no such units are installed in the DEC or DHN heat layers of the ESTD system. For this reason, we added the possibility to allocate different *HeatSlack* prices for each heat layer.

In more concrete terms, the idea is to create a new parameter *HeatSlackPrice* for each 'heat zone'. This would multiply the default *HeatSlack* price in the objective function. Then, by setting the default value of the *HeatSlack* at 1 €/MWh, the actual *HeatSlack* price becomes the value of *HeatSlackPrice*.

One question arises: how can one set the value of *HeatSlackPrice* in each 'heat zone'? We suggest in this work using a weighted average of the corresponding units in the ESTD system. The implementation of this method is detailed in Appendix B. In summary, the value for the 'heat zone' k: $HeatSlackPrice_k$ is determined based on the following formula:

$$HeatSlackPrice_k = \sum_j \frac{Production_{j,k}}{\sum_i Production_{i,k}} \frac{ResourceCost_j}{\eta_j} \tag{1}$$

where subscript k refers to a 'heat zone' (e.g. BE_DEC, BE_DHN or BE_IND). Then, subscripts i and j refers to each technology aggregated in the *HeatSlack* (e.g. boilers, geothermal heat, etc). $Production_j$ corresponds to the yearly energy produced by the unit j (MWh/year). $ResourceCost_j$ is the cost of the resource used in technology j (€/MWh). η_j represents the efficiency of the unit j. As a result, the *HeatSlackPrice* is set for each MWh of heat produced, as the heat price (and not the resource price) is the decision maker for the dispatch optimisation in Dispa-SET.

In practice, it is possible that the *HeatSlackPrice*, as computed with equation (1), still leads to incoherent output. For example, the *HeatSlack* production might correspond to a consumption of resource higher than its availability in ESTD. This needs to be avoided to ensure a coherent soft-link. Therefore, in such a situation, the *HeatSlack* price needs to be increased up to a value for which the *HeatSlack* production of the two models are the same. If this happens, the soft-link results will need to be interpreted with care regarding the OPEX of the system.

Finally, if the use of *HeatSlack* is not allowed in a 'heat zone' k, one can set the $HeatSlackPrice_k$ to large values (e.g. 1 000 000 €/MWh). This avoids any *HeatSlack* production in this zone. As Dispa-SET optimises the economical dispatch of its heat production units, it will avoid at all costs the use of a *HeatSlack* with a very high price .

2.3 Soft-link

This work describes a bi-directional soft-link between an ESOM (EnergyScope Typical Days (ESTD)) and an UCED model (Dispa-SET). There are two main steps in this soft-link.

Firstly, the output energy system of the ESOM is used as input of the UCED model. This first step is depicted in Figure 8. As the two models differ, some data processing is required. The data have to be processed so as not to lose, or alter, information between the outputs of the ESOM and the inputs of the UCED model. After running the optimisations, the differences between the outputs of the two models can be investigated (yearly production, $CO_2 - eq$ emissions, total costs, etc). Additionally, the Dispa-SET model will provide the user with insights on the adequacy of the power system. To investigate all of the above, we defined indicators which are described in the next sections.

Secondly, to improve ESTD, we need to gather more information which is done through a parametric study applied on Dispa-SET. The latter is described in section 2.3.2. Based on the results from Dispa-SET and the parametric study, new constraints are added to ESTD. This is represented by a feedback loop (depicted in Figure 14) which justifies the name 'bi-directional' for the soft-link we present here. The purpose of these constraints is to improve the power system in terms of adequacy. This process is run iteratively, if necessary.

Later in this section the whole soft-link methodology is presented in details. This will cover (i) the STEP 1 (running both models, data processing, analysis of the outputs of Dispa-SET), (ii) the definition of the indicators used to analyse the outputs of Dispa-SET, and (iii) the STEP 2 (run a parametric study with Dispa-SET, implement new constraints in EnergyScope TD, then run the process iteratively until the requirements of adequacy are met). At the end of this section, the limitations of the methodology are listed.

2.3.1 STEP 1: Running the models

The first part of the bi-directional soft-link consists of processing the output system from ESTD, so that it can be used as input in Dispa-SET. Then the outputs from the two models are analysed with indicators defined in the next sections. These steps are represented in Figure 8.

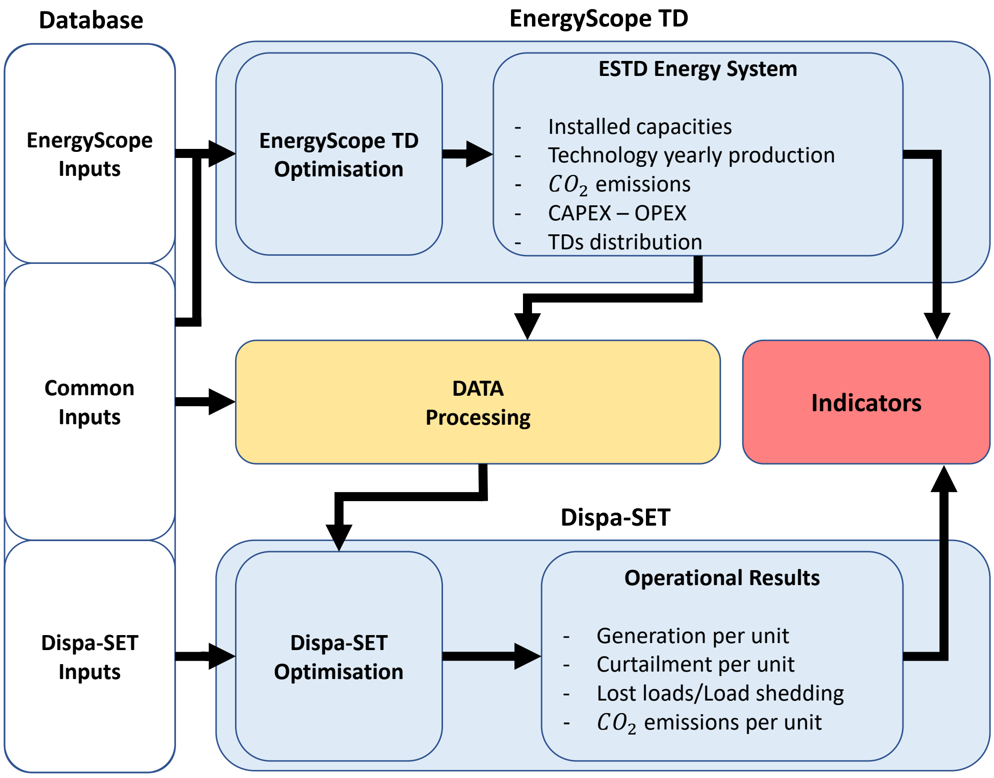

Figure 8: Schematic representation of the STEP 1 of the soft-link. We input data into both models. Outputs from EnergyScope TD are processed to be used as input in Dispa-SET. The results from both models are analysed with indicators defined in section 2.3.1.

To give an overview of the soft-link, it is useful to look at the five main parts of Figure 8. 'EnergyScope TD' gathers all the elements related to the ESTD optimisation and the output energy system. An equivalent box is dedicated to Dispa-SET. In the middle of the figure, 'DATA processing' represents all the tools used to create the Dispa-SET inputs. On the left of Figure 8, the 'Database' part is an inventory of all of data used in this soft-link, whether they concern EnergyScope TD, Dispa-SET or both models. Finally, the 'Indicators' box gathers the analysis and conclusions based on the results of the two models, using indicators defined in section 2.3.1.

We can now describe the different parts of Figure 8 in depth. 'The Database' box contains inputs related to ESTD, Dispa-SET or both ('Common Inputs'). The latter are adapted from the format of ESTD to the format of Dispa-SET, via the 'Data processing' tools. The main common inputs are the electrical and heat end-use demands, and the RES availability factors. The 'EnergyScope Inputs' are for example political or ecological constraints, mobility related parameters, etc. In other words, anything that is user-defined to specify a particular scenario. The 'Dispa-SET Inputs' include anything related to the higher level of resolution which ESTD does not take into account (e.g. operational features for each technology, prices for load shedding or lost load, etc.).

The ESTD optimisation provides outputs such as installed capacities, the yearly production of each technology, etc. The majority of these elements will be used as inputs of the Dispa-SET model after some data processing (represented in Figure 8 as

'Data Processing'). The data processing is necessary to solve issues related to format and representation of energy sectors (e.g. the electro-mobility will be considered as an additional load in the Dispa-SET model). Then we can run the Dispa-SET model which will give information on the unit dispatch (production, $CO_2 - eq$ emissions) and adequacy of the power system (lost loads, load shedding, etc). Indicators allowing the analysis of these information are described in section 2.3.1.

The next sub-sections will present in depth (i) the data processing (of the ESTD outputs to be used as inputs in Dispa-SET) and (ii) the indicators defined to analyse the outputs of Dispa-SET.

Data Processing

Based on the established interface in Figure 8, we can detail the way data are processed between EnergyScope TD and Dispa-SET. Using this link, we obtain a coherent representation of the energy system in both models without inducing systematic errors. The processing is essential to resolve differences between the two models in terms of:

- Data format
- Nomenclature
- Energy sectors representation
- Losses
- Import and exports of electricity
- Technology resolution

Format differences need very little processing. For example, the features (Coefficient Of Performance (COP), efficiency, storage (dis)charge time,etc) of the technologies implemented will have the same values in ESTD and Dispa-SET but are presented in different formats. In ESTD, the efficiency and/or COP of each technology can be extracted from a matrix. In Dispa-SET, a database, populated with the individual units of the power system, specifies directly the efficiency for each unit. Another example is the end use demand. In the ESOM, this is specified with a fixed component (a base load) and a varying component, whereas in the UCED this is specified as a single hourly time series.

Processing is also needed where nomenclature differs. Most of the technologies in EnergyScope TD can be inputted into Dispa-SET but using different names. Relevant correspondence had to be established prior to implementing the soft-link. An example is given in Figure 11, where the unit called 'CCGT' (Combined Cycle Gas Turbine (CCGT)) in Energyscope TD, is called a 'COMC' in Dispa-SET. An exhaustive list can be found in Appendix A.4 (see Table 22).

In addition, the representation of the energy sectors (electricity, heat and mobility) is different in the two models. Dispa-SET being an UCED model, its focus is on the electricity sector. For instance, mobility is not specified *per se* but electro-mobility is taken into account as an additional electrical load. Hence, in this soft-link, units that consume electricity but that are not considered in the version of Dispa-SET used in this work (e.g. Power to Gas (P2G)) are taken into account. Figure 9 illustrates the case of electro-mobility and H_2 electrolysis added as an additional load to create the Dispa-SET electricity EUD. The load added corresponds to the consumption of these units, based on the typical days distribution in the ESTD optimisation.

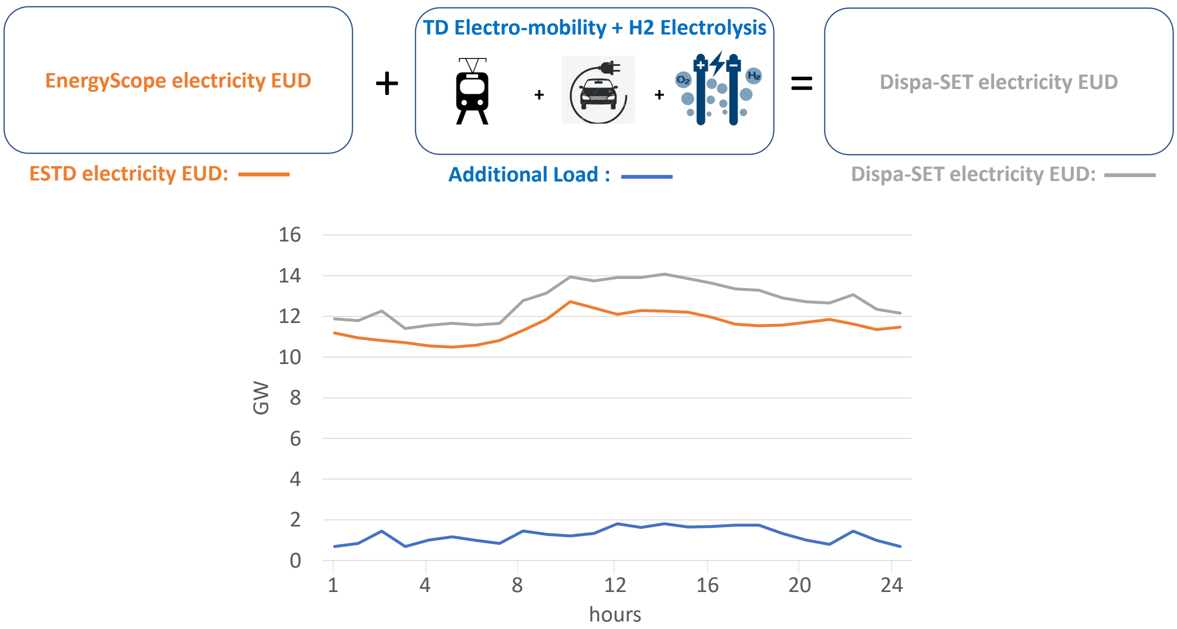

Figure 9: Schematic representation of the Dispa-SET electricity EUD: electro-mobility, P2M (BEV) and P2G (H_2 electrolysis) are added as electrical load to the ESTD electrical EUD. These loads are re-build from the typical days distribution of ESTD.

Another disparity in sector representation concerns the Low Temperature (LT) heat layer. Recall, modifications were made to Dispa-SET to distinguish between the LT and the High Temperature (HT) layers (resulting in the *Dispa-SET_NewZones* version). In ESTD, a single LT heat demand time series ($LT_{EUD}(h)$) is required as input. The first model optimises the split between centralised (DHN) and decentralised (DEC) LT heat (see Figure 10). For the *Dispa-SET_NewZones* inputs, we provided two different LT heat demand time series: $DEC_{EUD}(h)$ for DEC LT heat and $DHN_{EUD}(h)$ for DHN LT heat. The construction of these two time series is done by splitting the ESTD LT heat demand time series, by means of a multiplying factor $f_{DEC\_EUD\_Perc}$:

$$f_{DEC\_EUD\_Perc} = \frac{DEC_{EUD\_year}}{DHN_{EUD\_year} + DEC_{EUD\_year}} \tag{2}$$

with DHN_{EUD_year} and DEC_{EUD_year} the yearly LT heat EUD covered by DHN or DEC heat generation units in ESTD. Note that eventually, the heat productions covered by DHN or DEC technologies are equivalent in the two models.

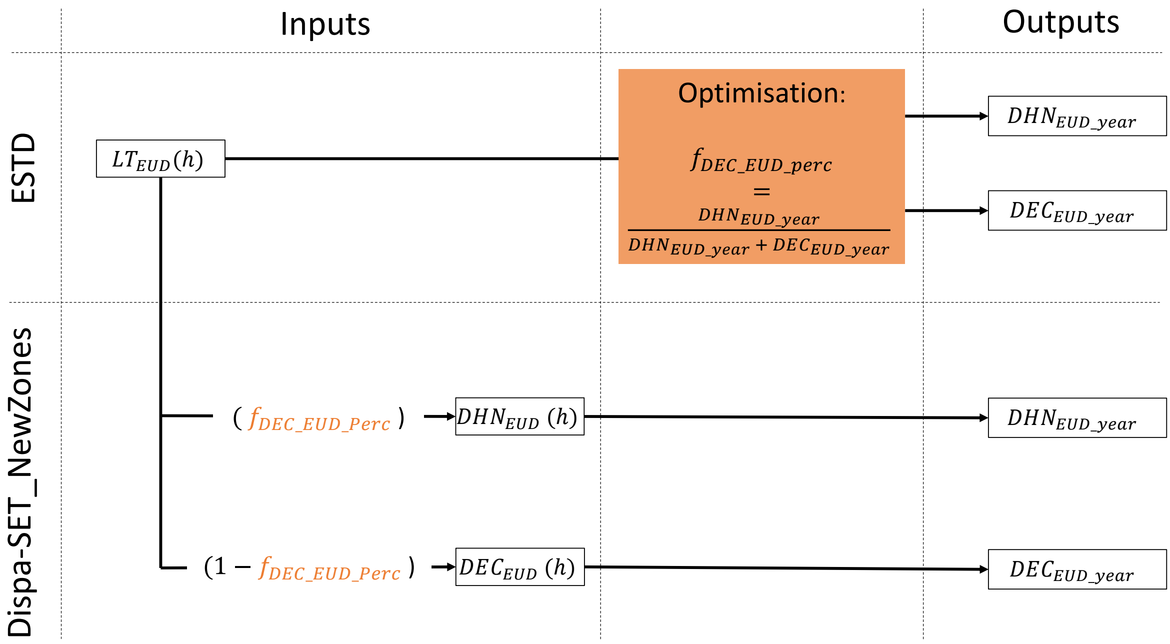

Figure 10: Construction of the DEC and DHN LT heat EUD for Dispa-SET. The LT heat demand is split during optimisation in ESTD into a centralised (DHN) and decentralised (DEC) demand. These demand are used as input in *Dispa-SET_NewZones*.

As illustrated in the previous figure, the Dispa-SET DHN and DEC LT heat demand time series are processed with the following equations:

$$DHN_{EUD}(h) = LT_{EUD}(h) * (1 - f_{DEC\_EUD\_Perc}) \tag{3}$$
$$DEC_{EUD}(h) = LT_{EUD}(h) * f_{DEC\_EUD\_Perc} \tag{4}$$

Next, losses need to be considered as these are not modelled in the same way in the two models. They need to be taken into account for both (i) electricity and (ii) centralised heat generation. The losses concern each kWh produced (and not consumed). In terms of the electricity losses, ESTD considers a constant grid loss[5] where Dispa-SET does not. To take these losses into account in the latter, the electrical EUD is increased. The original electrical EUD is multiplied by a factor equal to ratio between the ESTD yearly electricity production and the yearly electricity demand (details in Appendix C). Next we have to consider losses linked to the use of the DHN heat layer in ESTD. Those losses are computed as a percentage[6] of the DHN heat produced. In Dispa-SET, these are taken into account in a similar way to the electrical losses: the original DHN heat demand is multiplied by a factor representing the additional losses (details in Appendix C).

Regarding imports, as a reminder, ESTD allows electrical exchanges with the outside of the studied zone. It is optimised during simulation. In contrast, the Dispa-SET model

[5]typically: 4.7 %
[6]typically: 5%

usually specifies these as a fixed time series. For the soft-link, one possibility would be to provide Dispa-SET with an imports time series, built based on the ESTD output Typical Days distribution. This constrains the dispatch in Dispa-SET. To avoid that, we populate the Dispa-SET power system portfolio with an extra power generating unit which represents the imports of electricity. This unit is associated with a fixed price which corresponds to the price of importing electricity from the outside of the system in ESTD. Also, all the operational constraints of this unit are neglected, representing an ideal electricity source.

Finally, when coupling an ESOM and an UCED model, technology representation will differ, as the purpose of the two models is inherently different. As a reminder, ESOM focuses on a general description of technology, whereas the UCED model details the unit commitment and dispatch. These differences go hand in hand with the difference in temporal resolution: ESOMs, as they disregard operational constraints, do not need high-temporal resolution and *vice-versa*. Or as Collins stated: "technical constraints are dependent on the temporal representation" [4]. So how can we go from one technological representation to the other? This is done through a database which, for each technology and fuel used, can detail related operational constraints. The data base used comes from a paper on the soft-link of Dispa-SET and the TIMES model [10]. This ensures a good transition from technology type representation to a unit representation. From the ESTD energy system, we first make a correspondence between the models terminology as explained earlier. Then the global installed capacity of each technology is split in an integer number of units, according to typical power capacity from the database. Eventually, other inputs needed in Dispa-SET are taken from the same database. An example of these three steps is depicted in Figure 11 in the case of a CCGT unit.

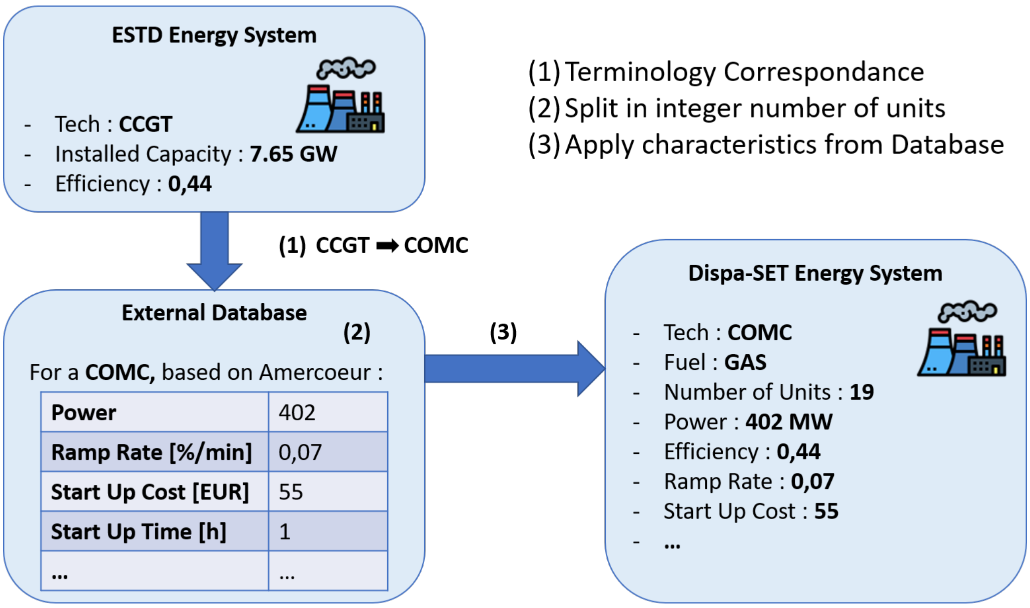

Figure 11: Schematic Representation of power plants data processing, from ESTD system to Dispa-SET Database. On the figure, a combined cycle is taken as an example. The ESTD system gives out the installed capacity as well as the efficiency. Data concerning operational aspects (ramp rate, start up cost,etc) come from an external database.

Post-Processing

Once the models have been run, results have to be post-processed in order to be compared. As the two models are different, we expect these results to diverge. The output from the UCED model will give insights in terms of operational dispatch and the adequacy of the system, as it has a greater temporal and operational resolution.

A formal framework of evaluation is defined through indicators. These indicators are listed in Table 1 and can fall in one of the following categories : (i) behaviour, (ii) adequacy and (iii) reliability.

Behaviour: what differences are apparent between the two models ?

The behaviour indicators (first part of Table 1) can highlight trends in the differences between the outputs of the models (e.g. regarding electrical storage, Dispa-SET does more cycles than EnergyScope TD). These trends give insights on the ESTD outputs and their interpretation.

On top of that, ESTD has several constraints that Dispa-SET does not take into account (e.g. total $CO_2 - eq$ emissions, resources availability, total costs). These indicators help investigate if the constraints are respected as well in the Dispa-SET optimisation.

Category	Metrics	Objective
Behaviour	Difference in yearly production per units Difference in yearly resources uses Number of start-ups per units Equivalent full discharge cycle per storage units Curtailment difference Total Costs Total $CO_2 - eq$ emissions	Not Applicable
Adequacy	Load shedding Loss of Loads Expectancy (LoLE) Energy Not Supplied (ENS)	See Table 2 < 3h < 0.2 GWh
Reliability	Minimum capacity margin	Not Applicable

Table 1: This is an exhaustive list of the indicators used to post-process results of the soft-link. Special attention is given to the adequacy indicators as they pose conditions for the feedback loop (next section).

Adequacy: can the energy system cope with the demand for the studied period ?

As explained earlier, the main purpose to soft-link the two models is to get insights on the adequacy of the system built by EnergyScope TD. Note that the adequacy is understood here in terms of balance between production and consumption, plus the tertiary frequency reserve of the power system.

According to Heylen et al. [11], there is no defined methodology to assess adequacy even though there is a multitude of adequacy indicators. In addition, some of those indicators rely on probabilistic analysis (e.g. Monte-Carlo method [12]), or focus on electrical grid related issues (defaults, loss of lines, etc). These are not implemented in the models studied in this work.

After consulting official reports from ENTSO-E[7] and the European Commission [13], [14], we selected the most appropriate indicators. Concretely, adequacy is checked through upper limits imposed on the (i) Loss of Load Expectancy (LoLE), (ii) the Energy Not Supplied (ENS) and (iii) the load shedding.

The LoLE represents the number of hours over the year where lost loads occur ([h]). In simple terms, load loss happens when the simulation fails: the power system is forced to reduce the demand because of a lack of power available. In such case, even the inclusion of demand side management is insufficient. The ENS keeps a record of the yearly total lost loads ([GWh/year]). Those two concepts are illustrated in Figure 12.

The load shedding represents a decrease of the demand (also called demand response) when it proves to be economically attractive. In reality, load shedding can be implemented via contracts with users who agree to reduce their electricity consumption. A load shedding price (€/MWh) is established between the user and the Transmission System Operator (TSO) for this service. Load shedding offers some flexibility to the system. As an example, it could be applied for one hour rather than switching on a power plant, which is expensive.

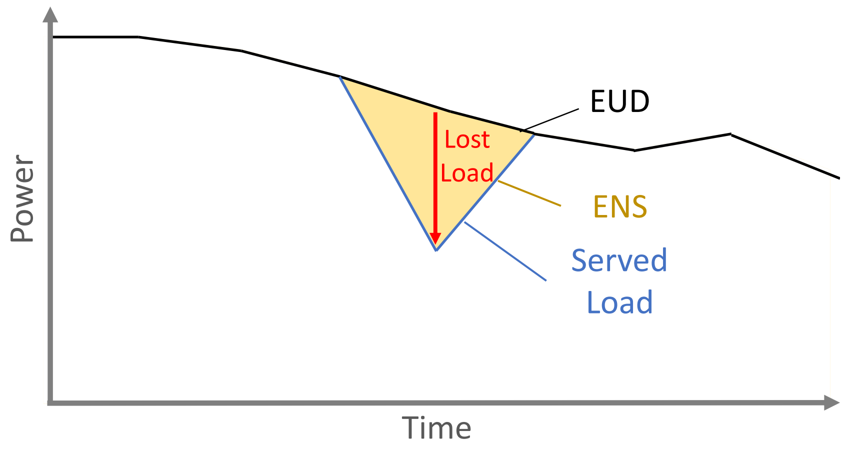

Figure 12: Graphic representation of two indicators used in this work: Lost Loads and Energy Not Supplied (ENS). If the system can not supply the demand, there will be a loss of load. The ENS corresponds to the integral of lost loads over time.

Upper limits for these indicators need to be defined in order to quantify the objective of adequacy. For the LoLE and ENS, the Belgian TSO (Elia) has defined standards (see Table 1).

For load shedding, as no standards are established by the European TSOs, limits were set based on projections made by Elia for future demand response market [12]. Different categories are defined depending on the maximum time this load can be shed throughout the year. As the projections are given as absolute values ([MW]) in Elia's report, they were normalised with the peak demand projection. This way, the criteria can be applied to any case study (see Table 2).

[7] European Network of Transmission System Operators for Electricity

Category of load shedding	Volume of load shedding in % of peak load
Max 2 hours per year	5.00
Max 4 hours per year	5.46
Max 8 hours per year	4.29
No limit	2.14

Table 2: Projection of future demand market response according to Elia 2030 projections [12]. Different categories are defined according to the time the load can be shed. The volume of load shedding allowed is normalised as a percentage of peak load. So, it can be applied to any EUD.

We used projections for the load shedding as in the future it is expected that the demand response market will increase. This is because energy systems will rely more and more on intermittent renewables, whose production is difficult to forecast.

Finally, if the adequacy indicators of the energy system comply with the limits set, the ESTD power system will therefore be considered as reliable and adequate. If this is not the case, a feedback loop needs to be applied to improve the adequacy of the power system. This will be described in the section 2.3.2.

Reliability: is the system robust enough to cope with of a variation of input?

To further assess the system, one can study the capacity margin. This represents the hourly available electrical power, expressed as a percentage of the electrical end use demand. Capacity margin has never been formally defined for energy systems with high electrification of the heat supply and a large installed storage capacity. Current definitions of capacity margins (which only take into account dispatchable unit capacity and peak electrical EUD) are not relevant to these systems (further explanations in Appendix C.2). By dispatchable, one understands technologies for which the power level can be controlled and varied (e.g. a gas turbine).

Given this deficiency, in this work the authors defined capacity margin $Capa_{marg}(h)$ for every hour h as described in equation (5), and depicted in Figure 13. The main concept behind this equation is that the available power is computed as the difference between the installed capacities of dispatchable units i ($Capa(i)$) and their actual production at hour h ($Prod(i,h)$). In addition, we consider that both the electricity stored and the flexible loads (e.g. a Heat Pump (HP) charging a thermal storage) influence the capacity margin positively (Sto_{elec} and $Load_{Flexible}$). The margin is defined as follows:

$$Capa_{marg}(h) = \frac{\sum_i (Capa(i) - Prod(i,h)) + \sum_j Sto_{elec}(j,h) + Load_{Flexible}(h)}{Load(h)} \quad (5)$$

where the subscripts i correspond to each dispatchable generation unit (no renewables, no nuclear). j defines every electrical storage unit. Finally, the term $Load(h)$ is defined as the electricity consumption at hour h, to which we substract flexible loads (e.g. heat and electricity storage). This way, the capacity margin represents a percentage of load increase that the system can cope with at each hour. Finally, no objective has been fixed regarding the capacity margin. This will simply be an indicator of the reliability of the system. It can be compared with today's capacity margin which is roughly 10%.

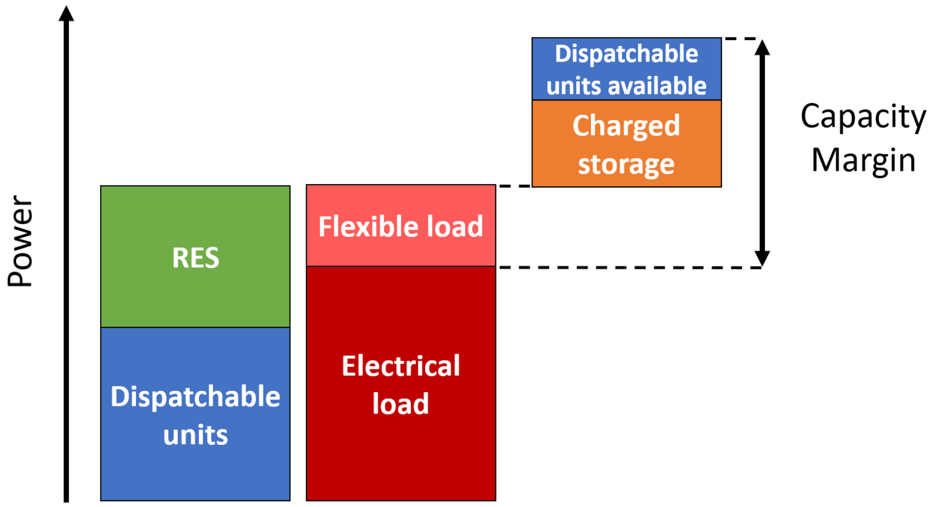

Figure 13: Graphical representation of the capacity margin definition, as defined in this work. This comprehend (i) a reliably available power capacity (e.g. gas turbines), (ii) the power discharge of electrical storage (if sufficiently charged), and (iii) flexible load (e.g. charging THMS through a P2H unit).

Finally, if the indicators of adequacy are higher than the margins which are set in Table 1, the ESTD system will need improvement. This is done via a feedback loop using the outputs from Dispa-SET to impose new constraints on the ESTD model.

2.3.2 STEP 2: feedback into the ESOM

The feedback loop has to solve issues of adequacy such as (i) a lack of reliable power capacity (inducing lost loads) and (ii) a lack of capacity reserve (inducing load shedding). These will be central to the feedback loop process.

Different possibilities were investigated to select the constraints to be introduced in the ESOM: (i) Direct method: drawing conclusions directly from the UCED model outputs or (ii) Parametric study: first carrying out a parametric study on the UCED model, and then adding new constraints to the ESOM. Table 3 shows a comparison of these two options:

Method	Pros	Cons
Direct method	Only one run of Dispa-SET	Requires a full analyse of the system Case dependent User dependent Intricate analysis
Parametric study	Automatic method (not case dependent) Convenient for complex systems No need for analysing the whole system	Multiple runs of Dispa-SET

Table 3: Comparison of two possible feedback loop methods.

As presented in the previous table, the 'Direct method' has limitations. The concept is to investigate the system via cross-units and cross-sectoral interactions. A disadvantage of this method is that it is highly case-dependent and left to the skills and judgement of the user. In addition, there is no guarantee that the conclusions will lead toward the global optimum. As an example, if the results of Dispa-SET show a lost load of 5 GW, we could populate the power system portfolio with an extra 5 GW of dispatchable units (e.g. a gas combined cycle). Increasing the power capacity by the same amount of lost load improves the adequacy but the resulting system does not correspond to the global optimum. To understand this, recall that the energy systems under study are complex, allowing cross-sectoral interactions and storage management. Because of this, the adequacy could be reached with a lower increase in power capacity (than the 5GW stated above). Experiments have been carried out to confirm this (see appendix D.1.1). In conclusion, the 'Direct method' requires a case-dependent analysis of the Dispa-SET outputs. And in the case of future energy systems with cross-sectoral interactions, these analyses could prove to be intricate.

The second option ('Parametric study', see Table 3), quantifies the lack of power capacity of the system by successive runs of the Dispa-SET optimisation. Each time, the electricity demand is lowered until the adequacy requirements are met. The advantages of this method is that it is an automated process, which is neither case-dependent nor user-dependent. However, the drawback is that it implies several runs of Dispa-SET, and increases computational time.

After testing these methods, the second one was selected in this work for its advantages listed above. Hence the soft-link methodology includes two feedback loops (see Figure 14). The first one is applied to Dispa-SET ('A') and the second one to EnergyScope TD ('B'). These two feedback loops will help us to tackle problems of (i) power capacity, to eliminate lost loads and (ii) reserve capacity, to decrease the load shedding.

The feedback loop 'A' applied to Dispa-SET focuses on lost load issues. The concept is the following: if lost loads are observed, this means there is not enough power capacity in the energy system. To quantify the lack of power capacity, we successively decrease the electrical demand in Dispa-SET by multiplying it by a factor $0 \leq K_{elec} \leq 1$. This step is iterated until lost loads are eliminated in the simulation. Then, to determine the reserve capacity needed, we assess the most critical period of load shedding which is the largest amount of energy shedded, in a continuous time period (see Figure 15).

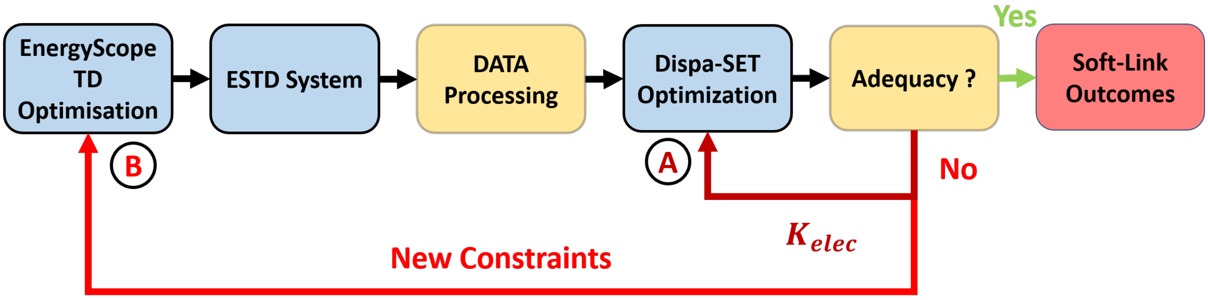

Figure 14: Schematic representation of STEP 2 of the soft-link. The former takes place in two steps: (A) A parametric study is run with the Dispa-SET optimisation to estimate the lack of power capacity which defines a factor K_{elec}. The latter is needed for (B) implementing new constraints in the EnergyScope TD optimisation. This improves the adequacy of the power system to meet the set requirements.

Once we have quantified the lack of power and reserve capacity, the constraints can be added to ESTD. The two constraints added in the model rely on different parameters: (i) K_{elec}, resulting from the parametric study of Dispa-SET, (ii) the largest amount of energy shedded (En_{shed} [GWh]) in a consecutive number of hours (Δt_{shed} [h]) (See Figure 15), (iii) a fixed parameter $Import\_Capacity$ representing the maximum power which can be imported from the outside of the zone studied and (iv) $Power\_Flex$, the flexible power capacity. The latter encompasses the dispatchable power generation units and the electrical import capacity, and is defined as follows:

$$\begin{aligned} Power\_Flex_{ini} &= \sum_{j}^{DispatchableTech} F_{j,ini} + Import\_Capacity \\ Power\_Flex &= \sum_{j}^{DispatchableTech} F_{j} + Import\_Capacity \end{aligned}$$

The subscript ini refers to the initial power system (i.e.: the one before the feedback loop is applied).

The new constraints implemented in ESTD are the following :

$$\begin{aligned} \sum_{j}^{ConstantElecTech} F_j + Power\_Flex &\geq \frac{Power\_Flex_{ini}}{K_{elec}} \\ (Power\_Flex - Power\_Flex_{ini}) * \Delta t_{shed} + Sto_{limit} &\geq En_{shed} \\ Sto_{limit} &\leq \sum_{k}^{StorageTech} F_{t,k} \end{aligned}$$

where F_j and $F_{ini,j}$ correspond respectively to the installed capacity of the tech j in the new and the initial system. $F_{t,k}$ represents the minimum storage level of technology k. Different categories of technologies are represented in the constraints: (i) $DispatchableTech$ corresponds to every units whose production can be controlled and varied (e.g. CCGT), (ii) $ConstantElecTech$ includes technologies whose electricity production cannot be easily controlled (e.g. Nuclear) and (iii) $StorageTech$ corresponds to all technologies used to store electrical energy (e.g. pumped hydro storage, lithium battery).

The first constraint increases the total power generation capacity, encompassing dispatchable or non-dispatchable units (e.g. nuclear power). This increment is based on

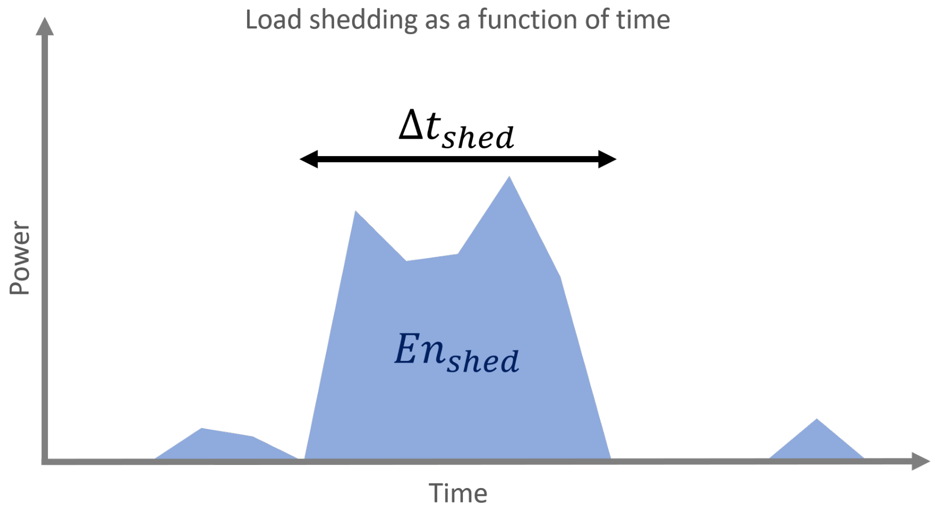

Figure 15: Schematic representation of the parameters En_{shed} and Δt_{shed} used in the feedback loop. These are determined based on the outputs of Dispa-SET and characterise the greatest quantity of load shedding (En_{shed}) in consecutive hours (Δt_{shed}).

the factor K_{elec}. Recall that the latter is determined by the parametric study to assess the lack of power capacity in the initial system.

The second constraint concerns the load shedding. Based on the biggest quantity of load shedded consecutively (En_{shed}, linked to a time period of load shedding Δt_{shed}), the optimisation has two options: (i) increase the $Power\_Flex$, in other words adding a power capacity equal to EN_{shed} / Δt_{shed} to the dispatchable units or (ii) set a quantity of energy stored available at any time (Sto_{limit}), equal to EN_{shed}. The way this equation is implemented has an advantage: it lets ESTD choose between adding dispatchable power, storage capacity or both.

The third equation ensures the minimum quantity of energy stored available at all time, in all electrical storage technologies jointly. Note that depending on the optimisation, the variable Sto_{limit} could be equal to zero.

Once the constraints have been included in ESTD, its optimisation is run again, resulting in a new energy system. After some data processing, the Dispa-SET optimisation can take place. Finally, the power system adequacy is checked again, and the whole process is re-iterated if necessary.

To summarise, the methodology proposed has several advantages: (i) it is automatic and applicable to any energy system, (ii) it introduces constraints in ESTD which represent the lack of power capacity and reserve capacity of the system and (iii) it allows the ESOM decide the optimal way to comply with the constraints. Two distinct feedback loops can be distinguished. The first one quantifies the lack of power capacity. The second one implements new constraints in EnergyScope TD. As a result, the 'initial' energy system is modified, to meet the adequacy requirements defined in this work.

2.3.3 Soft-link outcomes

Once the energy system has been modified and adequacy requirements are met, the differences between the 'initial' and 'adequate' system can be studied. This is referred to as the 'soft-link outcomes'. These include conclusions on (i) ESTD constraints and (ii) cost variations.

The ESTD optimisation has constraints that Dispa-SET does not have (e.g. limit on the $CO_2 - eq$ emissions). Post-processing is needed to ensure that these are respected. Then, the estimated price of the initial system changes due to (i) modification of the energy system (e.g. new technologies installed) and (ii) the dispatch operated by Dispa-SET. The latter can impact the operating costs if the productions of the power generating units are not the same in the two models.

The improvements in adequacy and cost variation can be taken into account in a Key Performance Indicator (KPI) we call $Cost\_of\_Adequacy$, defined as follow :

$$Cost\_of\_Adequacy = \frac{\Delta Yearly\_Cost}{\Delta ENS + \Delta En_{shed}}$$

This represents the cost of improving the adequacy of the system [€/MWh], with $\Delta Yearly\_Cost$ being the total cost difference between 'initial' and 'adequate' systems (including investment, maintenance and operations). ΔENS and ΔEn_{shed} represent the differences in total lost loads and total load shedding respectively between the two systems.

The discussion can be expanded further based on this measure, if we compare it to the load shedding and lost load prices. If it proves to be more expensive to improve the adequacy of the system than to shed loads, it will be economically interesting to increase demand response market.

2.4 Limitations

A soft-link methodology between two different models relies on premises which inevitably lead to approximations. The goal of this section is to go through all the limitations that need to be considered when using the methodology presented in this work. The limitations consider (i) model adaptations (ii) modelisation of the Power to Mobility (P2M) and Power to Gas (P2G) in the soft-link, (iii) imports and exports, (iv) the requirement of an external database to supply data linked to unit dispatch (needed in Dispa-SET), (v) outage factors (vi) the lack of standards regarding future power system adequacy.

Firstly, modifications were made to the Dispa-SET model so that its representation of energy sectors is closer to EnergyScope TD. Recall, these modifications were to (i) differentiate heat layers (LT and HT) and (ii) consider a different *HeatSlack* price for each heat layer. Even with these, we can still expect divergence. The first cause will be that thermal storage is implemented differently in the two models, as described in Sections 2.1.1 and 2.1.2. This relates especially to the DHN layer of the ESTD model, where several technologies can be linked to a centralised storage. In contrast in Dispa-SET, each heat generation unit is linked to their own storage. Another cause of divergence will be that resources can be used infinitely in Dispa-SET, but not in EnergyScope TD. One therefore needs to check in post-processing whether or not a resource is used in Dispa-SET beyond the availability limit set by ESTD. This applies especially to the representation of the

HeatSlack. The latter has a different price fixed in each heat layer. The price can be set higher to reduce the *HeatSlack* production in each layer. In this way, we can in theory have the *HeatSlack* production within the constraints. But this only works if the heat layers are independent from each other and this is not always the case. A short example is illustrated in Appendix C.3.

Secondly, there is a difference between the models in the representation of (i) Power to Mobility (P2M) and (ii)Power to Gas (P2G). In EnergyScope TD, different fuels are implemented (fossil fuel, H_2, synthetic fuels, ...). Notably, synthetic fuels have a role to play in the energy transition [15] (e.g. storage or energy imports/exports). In our version of Dispa-SET, only electro-mobility and hydrogen production (electrolysis) are taken into account as a time series of supplementary electrical loads. These time series are built based on data from the EnergyScope TD typical days, which does not allow Dispa-SET to optimise P2M. P2M and P2G have been implemented in other versions of Dispa-SET. Using these versions can greatly improve this soft-link.

Thirdly, the soft-link requires a file containing all the operational features linked to every technology, such as power ramp, ramping cost and others. It is difficult to generalise this data among different units of the same technologies. For example, the ramp rate of a Gas Steam Cycle may change from one plant to another. The database we used comes from Pavicevic, 2020 [10].

In ESTD, an outage factor (c_p) is defined for each technology. This limits the yearly production to mimic outages and maintenance. For example, a geothermal installation of 4 MW with $c_p = 0.85$ can only produce an equivalent of $\frac{8760*0.85*4}{1000} = 29.78GWh$ over a year. In Dispa-SET, outages need to be specified as a time series, with hourly values between 0 and 1. Imposing an hourly outage value based on the ESOM production will impact the dispatch of the UCED and therefore the outputs. For this reason, we allow the UCED to run its dispatch, we then post-process the data to check whether or not the outage factors are respected.

Another limitation concerns the requirements of adequacy set in this work. As explained in Section 2.3.1, we defined indicators to assess the adequacy of the power system based on Dispa-SET results. However, there are no agreed uniform standards to assess a power system adequacy. Each Transmission System Operator (TSO) has its own best practice and rule of thumb. Moreover, we expect the requirements of adequacy to change in the near future, with growing integration of RES and the implementation of both short and long-term storage solutions.

Finally, another limitation concerns the constraints imposed on ESTD. These require the system to install either more dispatchable units or a greater capacity of storage. This poses two problems: (i) it does not take into account any other solution ESTD could find (e.g. power-to-X and X-to-power) and (ii) not many dispatchable units are represented in EnergyScope TD. The soft-link would be greatly improved by implementing more dispatchable technologies with low investment costs and operational expenditures.

3 Study cases description

Once the soft-link is established, simulations can be carried out. The case studies presented in this work focus exclusively on the Belgium energy system and are largely inspired by Limpens (2020) [3]. The different cases are (i) 'Belgium: high RES share': Belgium with a limit on $CO_2 - eq$ emissions and considered as an island and (ii) 'Belgium: energy mix': an energy system relying on a mix of technologies which could enable the Belgian energy transition. Figure 16 provides a global comparison of the two cases.

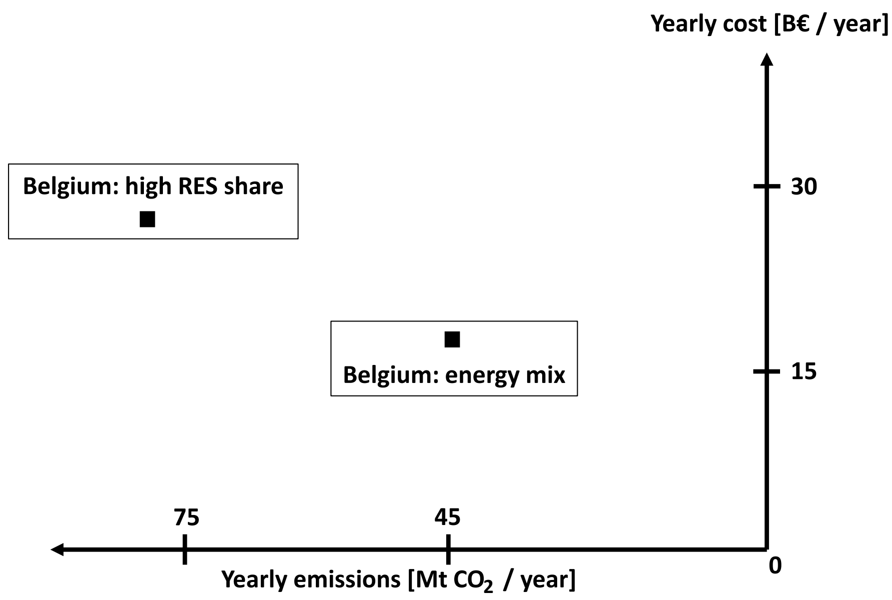

Figure 16: Graphical representation of the study cases. For reference, the 2015 Belgian energy system has a GWP of roughly 150 $MtCO_2/year$ (figure inspired from [3]).

These cases will give insights on soft-link outcomes which can be obtained from the feedback loop. Comparison will be made between the soft-link outcomes of both cases.

Studying adequacy through a Unit Commitment and Economic Dispatch (UCED) model implies considering the amount of load shedding and lost loads. Dispa-SET defines whether or not a load is shed or lost based on a defined price (indicated in Table 4). These prices have been set based on figures from Elia [16].

Parameters	**value**
Load Shedding Cost [€/MWh]	1 000
Lost Load Cost [€/MWh]	100 000
Admissible load Shedding per hour [% of load]	5

Table 4: Study cases: user defined parameters.

Recall that the soft-link only considers heat and electricity which is the focus of the next sections. More technologies are represented in EnergyScope TD than used in this soft-link (e.g. mobility, P2G, etc). However, some of them are considered as an additional electrical load (e.g. : H2 electrolysis, electro-mobility).

3.1 Belgium: high RES share

The first case study presented in this work is based on a projection of the Belgian energy system meeting the Global Warming Potential (GWP) limit of 73000 $ktCO_2-eq$ emissions per year. As a result of the GWP limit, the system provided by ESTD produces more than 60% of its electricity with RES units.

The main user-defined parameters have been set as described in Table 5. The constraints on CO_2 emissions, resource prices and the absence of nuclear power, are identical in ESTD and Dispa-SET.

Recall the computation of the *HeatSlack* prices need special attention, as Dispa-SET does not model a limit on resource availability. For this reason, the IND *HeatSlack* price had to be artificially increased to 37.85 €/MWh[8]. On top of that, there are no *HeatSlack* technologies implemented in the DEC and DHN layers. As a consequence, the corresponding prices were set to 1 000 000 €/MWh, to prevent the use of *HeatSlack* in these layers.

EnergyScope Parameters		**value**
CO2 emissions limit [$ktCO_2-eq$]		73 000
Minimum share of RES [%]		0
Other constraints		No nuclear No imports
Price of RESOURCE [€/MWh]	Gas	41
Dispa-SET Parameters		**value**
Price of *HeatSlack* [€/MWh]	DEC	1 000 000
	DHN	1 000 000
	IND	37.85
Reservoir Initial and Final Level initial		0.5

Table 5: User-defined parameters for the scenario 'Belgium: high RES share'. The price for the DEC and DHN *HeatSlack* to an exorbitant value to keep the simulation from using them.

With these parameters, the Belgian energy system as provided by EnergyScope TD is depicted in Figure 17. A large proportion of the power production are renewable units such as wind turbines or photovoltaïc panels. In addition, a combined cycle plant and a Combined Heat and Power (CHP) unit (both running on gas) are implemented, thereby giving flexibility. Finally, a big lithium battery capacity (53.5 GWh) is installed, next to a 5GWh Pumped Hydro Storage (PHS) unit.

[8]the price initially computed, as described in section 2.2, was of 32€/MWh

Regarding the heat layers, the decentralised (DEC) and centralised (DHN) heat productions are both handled by an equivalent of 29 GW of heat pumps. They are also both equipped with Thermal Storage (THMS) units. Note that the capacity of the DHN storage is extremely large: 22 TWh. The industrial (HT) heat production relies on four technologies: a CHP unit, 5 GW of electrical resistance (IND DIRECT ELEC) and two boilers (running respectively on wood and waste). The latter will be part of the IND *HeatSlack* in Dispa-SET.

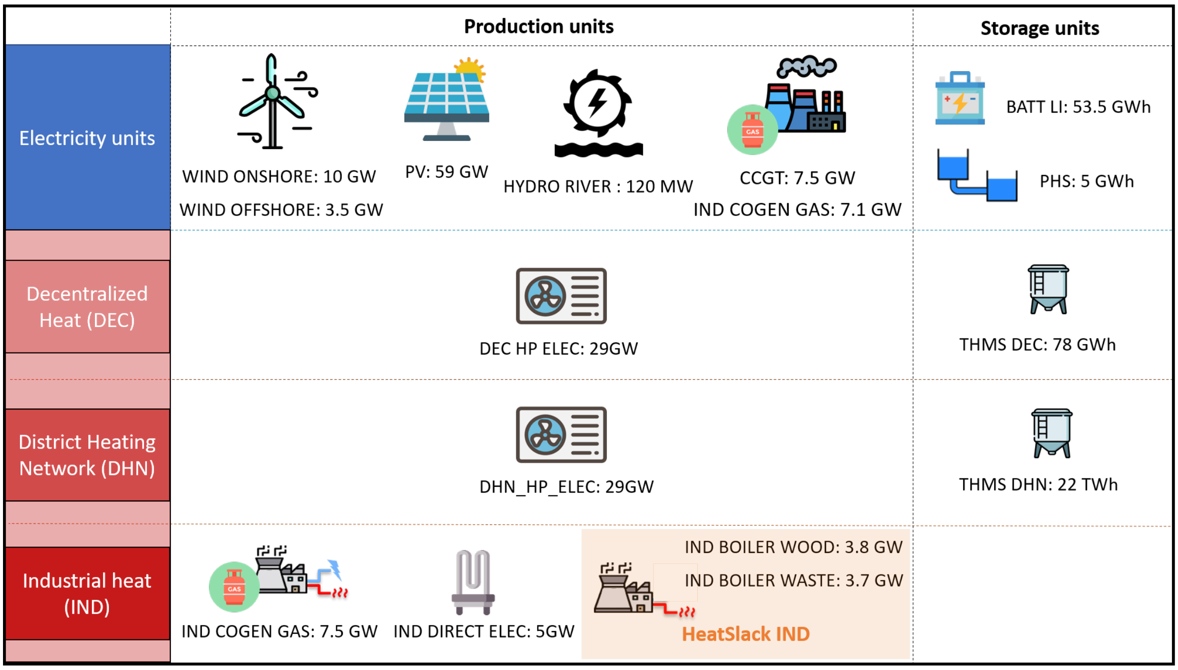

Figure 17: Energy system studied in the scenario 'Belgium: high RES share'. the dispatchable units (a combined cycle and CHP unit) both run on gas. A large storage capacity is also instaled for the electricity layer (58 GWh in total), for the decentralised (78 GWh) and centralised (22 TWh) heat.

The Dispa-SET energy system is equivalent to that depicted in Figure 17 but it excludes industrial heating. The boilers running on wood and waste are implemented as *HeatSlack* in Dispa-SET.

3.2 Belgium: energy mix

The second energy system investigated is one suggested in Limpens (2020) [3] for the Belgian energy transition. This scenario achieves low $CO_2 - eq$ emissions at an affordable cost.

This mix of technologies relies on several hypotheses: (i) an abundant potential of solar energy (10% of Belgian land area), (ii) extending the lifetime of the nuclear power plants, (iii) a potential of 8 GW of geothermal energy (split between electricity and centralized heat generation), (iv) an extra offshore wind potential of 3.5GW (the total reaching 10 GW), (v) doubling the electricity import capacity to 9 GW, and (vi) allowing the imports of renewable fuels (bio-fuels, synfuels, etc..).

The user-defined parameters are shown in Table 6. A distinction is made between the parameters set for the optimisation of EnergyScope TD and Dispa-SET. Prices of the different resources (which are the same in both optimisations) as well as the price of the *HeatSlack* for the different layers are defined. The price of *HeatSlack* has been increased to 2.6 [€/MWh] in the centralised low temperature (DHN) heat layer in order to make the production match in the two models. This is because the centralised LT layer is supplied by a geothermal unit of 4GW, with a null resource cost. If the price is set to 0, the DHN *HeatSlack* would exceed an annual production of $4 * 8760$ GWh, which is incoherent.

A fixed price has been set for the electricity import in Dispa-SET. This price is identical to the one specified in EnergyScope TD.

EnergyScope Parameters		**value**
CO2 emissions limit [$ktCO_2 - eq$]		40 000
Minimum share of RES [%]		0
Price of RESOURCE [€/MWh]	Uranium	3.87
	Electricity import	84.3
Dispa-SET Parameters		**value**
Price of *HeatSlack* [€/MWh]	DEC	1 000 000
	DHN	2.6
	IND	32.7
Reservoir Initial and Final Level initial		0.7

Table 6: User-defined parameters for the scenario 'Belgium: energy mix'. The price for the DEC *HeatSlack* is exorbitant to keep the model from using it.

The total energy system is depicted in Figures 18 and 19. The power system portfolio is mainly based on renewable energy. These comprise wind generation units (20 GW), Photovoltaic (PV) (14.9 GW), geothermal (4 GW) and hydro run-of-river (120 MW). The storage is ensured through the PHS (5.83 GWh) in the soft-link[9]. The rest of the electrical generation is based either on nuclear energy (5.6 GW) or electricity imports.

About the latter, they are modelled as a fictive power plant (as explained in section 2.3.1). Concretely, this unit is characterised by an efficiency of 100% and has no operational constraint. Finally, it is running on a fuel for which the price is equal to the fixed price for electricity import in ESTD (84.3 €/MWh).

[9]however, there were 16.7GWh of BEV installed in the ESTD system

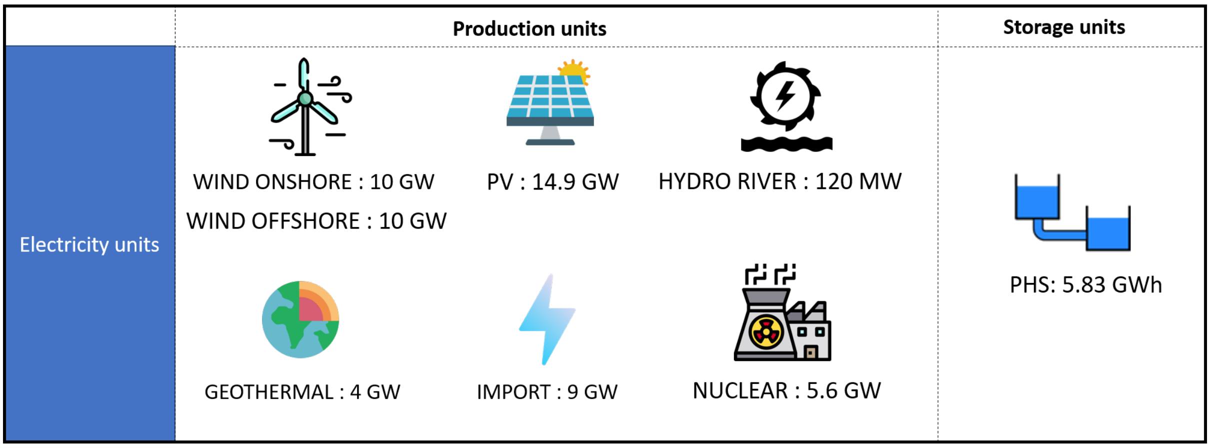

Figure 18: Representation of the power system portfolio. Most of the power capacity relies on renewable sources (roughly 39 GW). In addition, electricity import and nuclear energy are a part of the energy mix.

All of the heat layers have a Power to Heat (P2H) unit installed: heat pumps for the two Low Temperature (LT) layers (29.19 GW for the decentralised, and 5.45 GW for the centralised), and a resistance for the High Temperature (HT) (IND) heat layer (1.36 GW). Boilers are implemented to supply HT heat. These are running on gas (3.1 GW), coal (3.47 GW) and waste (0.97 GW) and will be represented as the *HeatSlack* in Dispa-SET. Thermal Storage (THMS) are also implemented for the two LT layers. The decentralised THMS amounts to 16.92 GWh where the centralised one rises up to 3.10 TWh. In addition, 4 GW of DHN geothermal technology is installed, which is represented as *HeatSlack* in Dispa-SET.

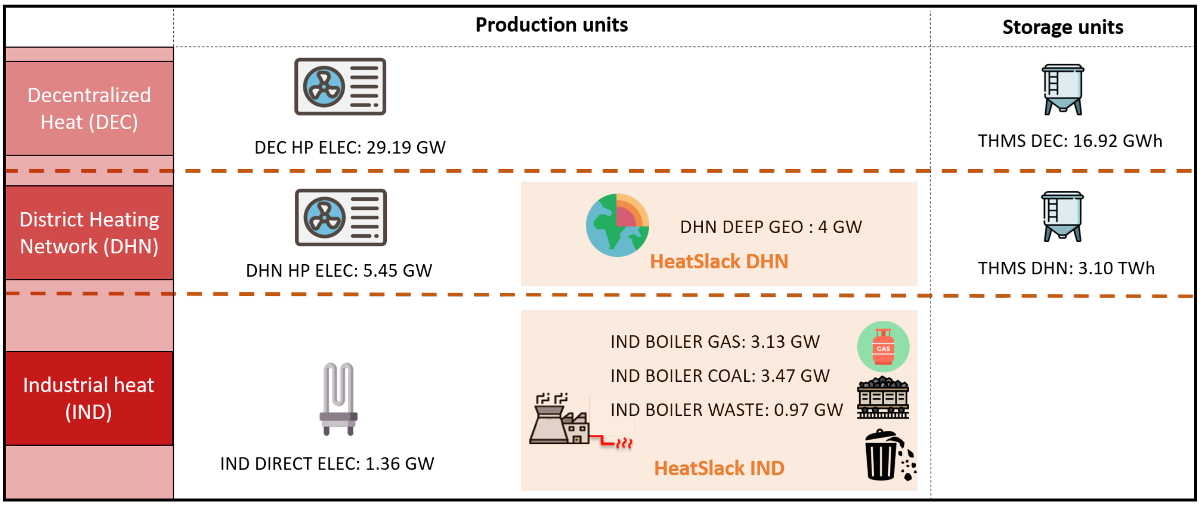

Figure 19: Representation of the heat generating unit in the different heat layer, and their respective storage. Every heat layer has a Power to Heat (P2H) unit. The two low temperature layers have Thermal Storage (THMS) installed. The industrial heat layer uses boilers (represented as *HeatSlack* in Dispa-SET) to supply heat as well as the P2H heat.

4 Results and analysis

In this section, the results about the study cases are presented. Analysis are made based on the previously defined indicators and conclusion are drawn regarding the feedback loop.

4.1 Belgium: high RES share

The energy system studied in this case relies on a high share (more than 60%) of renewable units to produce its energy (see description in section 3). The system might not be able to supply the energy needed for its load, hence not be adequate. This is where the feedback loop will be useful and improve the energy system adequacy.

So, before going into the details of the feedback loop process, the main simulation results are presented. In other words, the coming section highlights the main conclusions regarding behavior, adequacy and reliability indicators for the study case 'Belgium: high RES share'.

4.1.1 Soft-link: STEP 1

As a reminder, the first step of the soft-link consists in analysing the results of the two optimisation. The goal is to determine if the energy system provided by ESTD is adequate.

Productions analysis

The first indicators used for assessing the EnergyScope TD reliability are the total yearly productions of each unit. First, in Figure 20, one can see that globally the two models predict equivalent electricity productions for the units installed.

It is important to note that the temporal resolution has an impact on the RES representation. EnergyScope TD uses Typical Days (TDs), which minimize the error between the actual load duration curve and the one obtained with the TDs. It represents fairly well the RES on a year basis. However, the discrepancies between the two models grow bigger with smaller time horizon. Discrepancies can be observed on a day scale (see Figure 4), and on a monthly scale (see appendix D.1, Figure 37).

Concerning yearly energy production, small gaps appear for the plants running on gas. Firstly, the yearly production of the combined cycle (CCGT) in Dispa-SET exceeds by 2.5 TWh the one of ESTD. The reason of this mismatch is an over-estimation of the RES availability factors during winter month (see details in Appendix D.1). So, Dispa-SET compensates this deficit via the CCGT unit. Then regarding the CHP (IND COGEN GAS) unit, the production difference requires an investigation of the heat production.

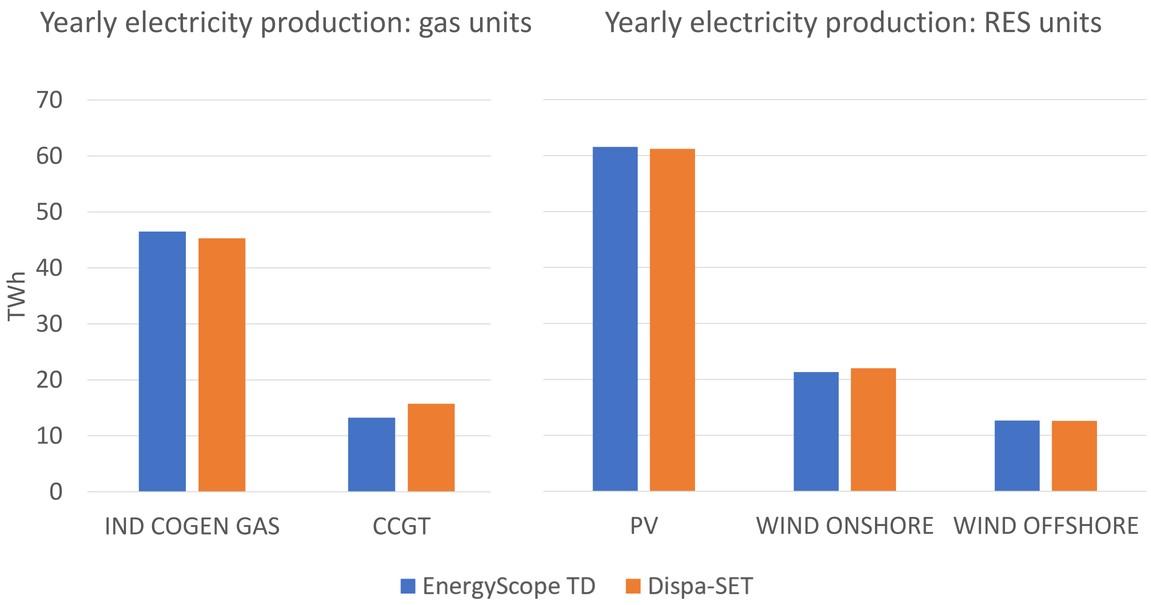

Figure 20: Electricity production per unit in both models for the scenario 'High RES share'. The production of the RES units match in the two model. Slight variations are observed with the energy production of the gas units.

See Figure 21 for the IND layer. The *HeatSlack* being used evenly in the two models, the production of the two other units have to be balanced. Starting with the electrical resistance, it is used twice as much in Dispa-SET than in ESTD. This is due to the fact that the renewable availability factors are slightly under-estimated in ESTD during spring and summer month (see details in Appendix D.1), compared to the availability factors used in Dispa-SET. Therefore, Dispa-SET has more free electricity at this period and will dispatch the IND heat generation to minimise the cost. On the other hand, ESTD having less RES available, it will increase the power of the CHP unit to meet the IND heat demand. As a result, the electricity produced by the IND COGEN GAS is superior in ESTD than in Dispa-SET.

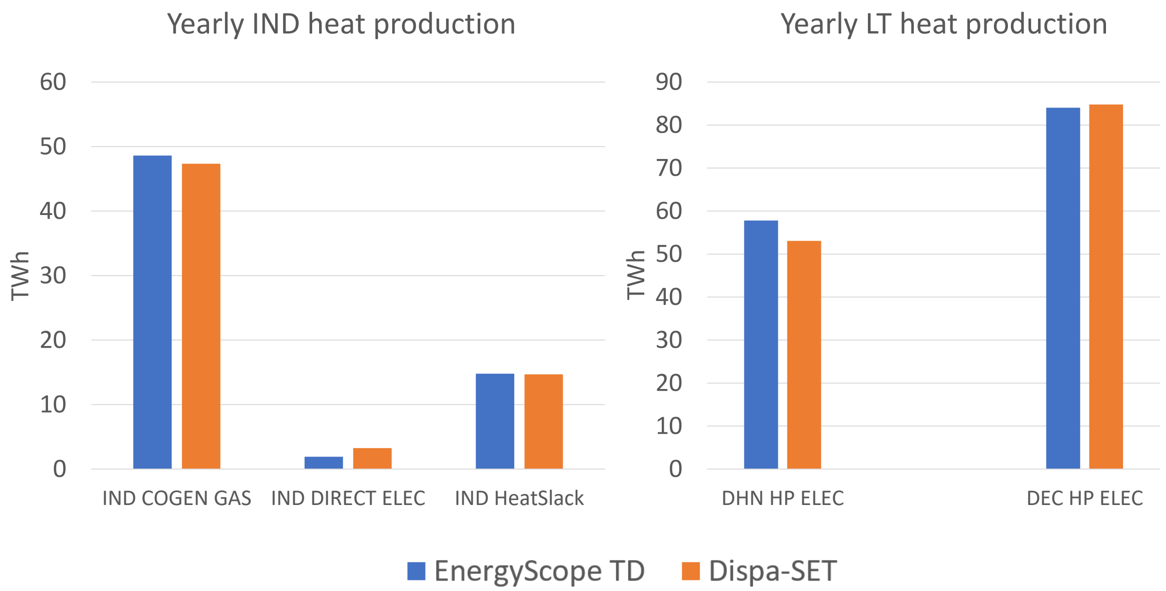

Figure 21: Heat production per unit in both models for the scenario 'High RES share'. The main production differences are noticeable for the CHP unit (IND COGEN GAS), the resistance (IND DIRECT ELEC) and the DHN heat pumps.

As far as the DHN heat productions are concerned, one can observe that the DHN heat pumps productions diverge in the two models. Based on Figure 22, two elements can explain this contrast: (i) different average DHN storage levels and (ii) different final DHN storage levels.

First, the DHN storage losses are computed as a share of the storage level at each our. We can see in Figure 22 that the storage level in Dispa-SET is always lower than the DHN storage level in EnergyScope TD. This translates in a lower average normalised level of the storage in Dispa-SET: 0.3, against 0.5 in ESTD. Hence, DHN storage losses in ESTD are 2.5TWh higher than in Dispa-SET. This is unexpected. One lead to explain this may be the optimisation horizon of several days in Dispa-SET (see section 2.1.2). The way it works is that it discard last days of the smaller optimisation horizons, resulting in differences between the actual and expected level.

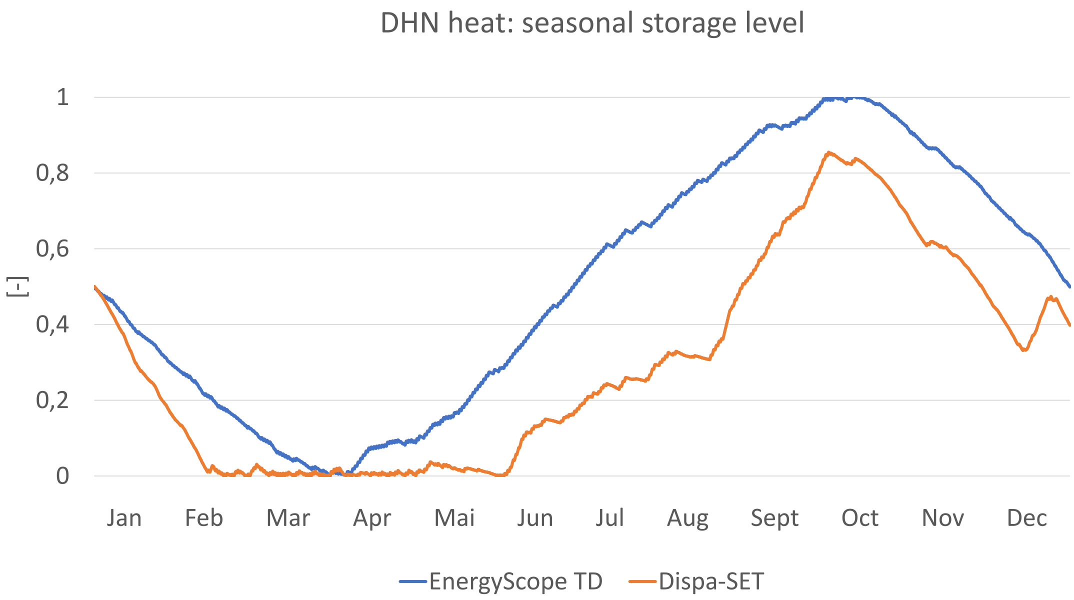

Figure 22: Centralised heat (DHN) storage level normalised with the storage capacity (22.1 TWh). The Dispa-SET is never filled to 100% of its capacity: the needed storage capacity might be over-estimated by EnergyScope TD.

Still about the DHN storage curves, one can notice in Figure 22 that Dispa-SET optimises the long term DHN storage differently than EnergyScope TD. This is due to two factors: (i) a higher temporal resolution in Dispa-SET and (ii) the economical dispatch. To due to low temporal resolution, ESTD underestimates the production from RES in summer. Conversely, this production will be higher in Dispa-SET. Then, when the optimisation carries out the dispatch, it is more profitable to use this energy directly in the IND DIRECT ELEC, than to run a IND COGEN GAS (which is the case in EnergyScope TD). Running the IND COGEN GAS to meet the HT demand has for direct consequence to have an excess electricity, which can be stored in the DHN THMS.

Finally, back to Figure 21, one can notice a gap between the yearly productions of the DEC heat pumps in the two models. Again, this is due to the average storage level. Here, the Dispa-SET average level is the highest (0.24 against 0.11 in ESTD). As a consequence, to compensate with the storage losses, the yearly DEC units production in Dispa-SET is 0.7 TWh higher than the one in ESTD. Another indicator is the equivalent full discharge cycles for the DEC heat storage: 145 in ESTD and 240 in Dispa-SET. To illustrate this, Figure 23 shows this during a few days in spring, Dispa-SET uses the DEC storage more intensively than ESTD.

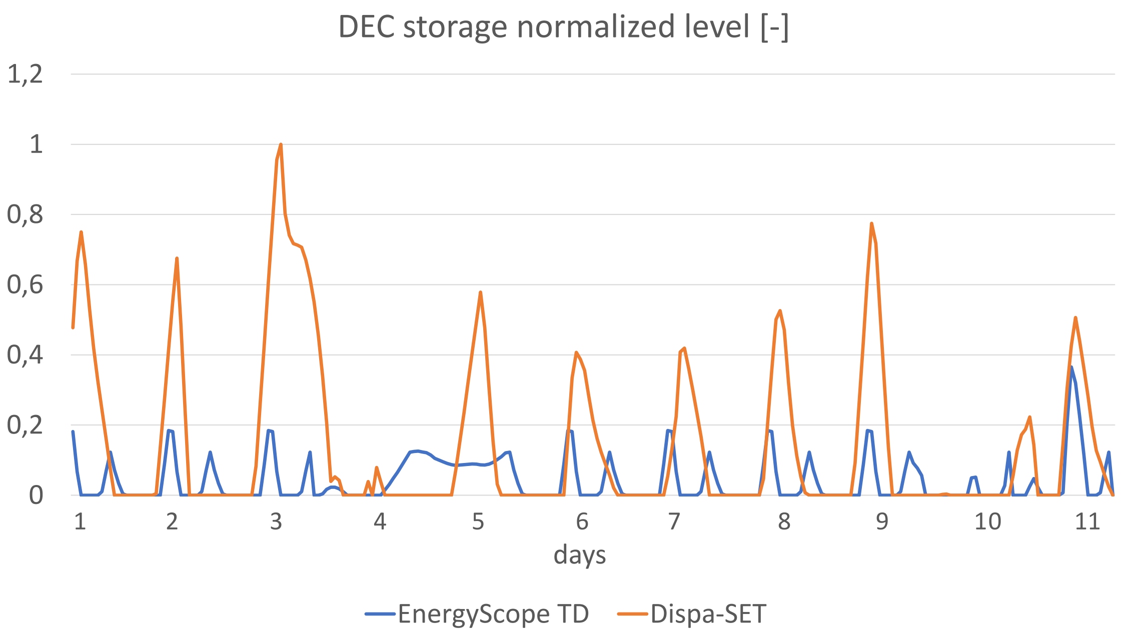

Figure 23: Decentralised heat (DEC) storage during a few days in spring. The level is normalised by the storage capacity (78.75 GWh). Dispa-SET uses more the DEC storage than ESTD.

To conclude about the low temperature heat productions in the two models, generally speaking, Dispa-SET uses more the DEC storage unit instead of the DHN storage unit, especially during winter and spring month. In contrast, ESTD will store DHN heat all over the year, hence reducing the use of the DEC storage. For the same reason as for the IND heat layer, this behavior difference may be due to the fact that Dispa-SET optimises a few days at a time, therefore it will choose the daily DEC storage technology rather than the long term DHN storage. This results in a lower DHN storage curve in Dispa-SET than in ESTD, which means lower storage losses and a lower DHN heat production overall.

Behavior indicators

Behavior indicators are presented in Table 7. First of all, the number of start-up of the gas units is way lower in Dispa-SET. This results from the optimisation of the dispatch which minimises expenses related to ramping and start-ups of the flexible units.

After that, we can investigate the 'equivalent full discharge cycles'. For all the short-term storage units (PHS, lithium batteries and DEC THMS), there are more cycles in Dispa-SET than in ESTD. This is directly linked to the use of typical days in ESTD reducing the temporal resolution, not representing daily variations in production. As a result, the use of the storage unit may be underestimated in ESTD.

The use of TDs may also explain why the total energy curtailed reaches almost 0.5TWh in Dispa-SET while it remains close to zero in ESTD. This energy represents around

0.5% of the total RES electricity production. With EnergyScope TD, the whole system is designed to absorb RES production based on the TD distribution. However, in Dispa-SET which uses hourly availability factors, RES production reaches peaks higher than what the TD predicts. As the ESTD system was built on TDs, these production peaks can not be absorbed by the implemented storage due to limits in the maximum charging power.

To interpret the operational costs[10] linked to the flexible units, the reader should note that ESTD only takes into account the resource costs in the OPEX calculation an no operational costs. For instance, although the IND COGEN GAS costs are similar in the two models, the ESTD total production is higher than the one in Dispa-SET. Coincidentally, the costs are the same for both models, but Dispa-SET takes into account operational supplementary costs (e.g. ramp-up and start-up costs). Regarding the CCGT, the total costs are different in the two models because of (i) higher production in Dispa-SET and (ii) the additional operational costs. All in all, there is an increase of 3.6% of the OPEX compared to ESTD, where 2.6% are due to operational costs (ramp-up, start-up, etc).

Finally, the $CO_2 - eq$ emissions are difficult to assess due to the fact that the *HeatSlack* unit aggregates the WOOD and WASTE boilers. It is then not possible to compare precisely the total emissions. However the emissions linked to these units only represent 4% of the total emissions in ESTD (79.3 $MtCO_2 - eq/year$). The production being comparable in both models, we can base our assessment solely on the gas consumption. Hence, ESTD overestimates GHG emissions since its total natural gas consumption is 1.5% higher than in Dispa-SET (combining CCGT and IND COGEN GAS consumptions).

Category	**Details**	**ESTD**	**Dispa-SET**
Start-up [-]	IND COGEN GAS	259	106
	CCGT	252	37
Eq full discharge cycles [/year]	Lithium Battery	132	200
	Pumped hydro storage	1.6	85
	DEC THMS	145	240
Curtailment [GWh]	All RES units	0.133	450
OPEX [B€/year]	IND COGEN GAS	4.38	4.38
	CCGT	0.87	1.07
CO_2-eq emissions [$ktCO_2$-eq/year]	Wood	97	n.a.
	Waste	1401	n.a.
	Natural Gas	33 780	33 270

Table 7: Behavior indicators for the scenario 'High RES share'. Dispa-SET has a much lower number of start-ups (as it operates more often at part load). Both the equivalent full discharge cycles of daily storage and curtailment are much higher in Dispa-SET. These two elements together hints that the higher temporal and technical resolution capture greater variability in the unit production. The system copes with this variability through the greater use of storage, which is not enough and results in higher curtailment.

[10]= resource price + additional operational costs

Adequacy indicators

In this study case, almost all the adequacy indicators do not meet the requirements set in this study. This result was expected, considering a system with large share of RES in the mix (more than 60%), and the lower temporal and technical resolution of ESTDs. Concretely, 47 GWh of Energy not Supplied (ENS) are observed, where the limit stands at 0.2 GWh only. This is a critical result showing a lack of dispatchable power capacity installed. Additionally, there is 18 hours of Loss of Load Expectancy (LoLE) according to Dispa-SET which exceeds the limit established of 3h per year.

Indicator	Value	Limit	Check
Load shedding [GWh]	110	5078	v
Max load shedding power [% peak load]	3.32	5.46	v
Lost of Load Expectancy [h]	18	3	x
Energy not Supplied [GWh]	47	0.2	x

Table 8: Adequacy indicators for the scenario 'Belgium: high RES share'. The ENS and LoLE do not meet the adequacy requirements.

Concerning the load shedding indicators, the total energy shedded and maximum power shedding are lower than the limits. However, some problems emerge when focusing on the admissible number of hours at each load shedding category. As illustrated in Figure 24, during 119 hours, the load shedding level stands between 2.14% and 4.29% of the peak load. Such an event is allowed only for 8 hours according to Elia projections for future power systems [16].

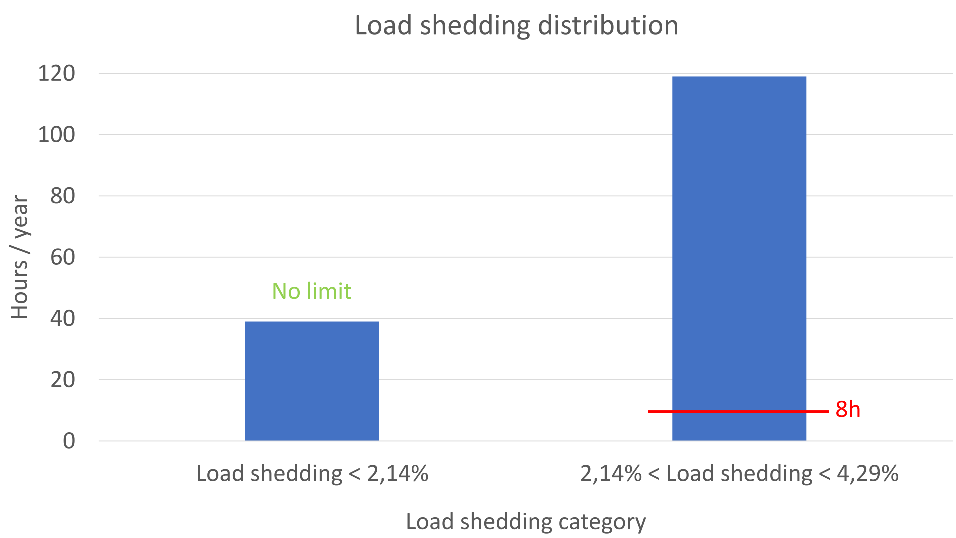

Figure 24: Number of hours of load shedding, per category of demand response as specified in Elia's report [16]. The adequacy criteria is not met as load shedding exceeds the limit for the category: 2.14% < load shedding < 4.29%.

Reliability indicators

In Table 9, one can see that during 93 hours (around 1% of the time), the capacity margin (as defined in section 2.3.1) drops below 10%. Also, the minimum capacity margin reaches 0.0 at some point. To explain those figures, two elements can be considered. First, the energy system under study could have lack dispatchable units capacity (e.g. Combined Cycle Gas Turbine (CCGT)). Second, this can result from the way this dispatch is performed in Dispa-SET. Indeed, the analysis of the capacity margin data showed a specific pattern: the capacity margin drops below 10% only during spring and summer, at the beginning of the day (between 6 and 9 am). It means that the optimisation allows the storage units to fully discharge, knowing that a peak in PV production is expected in the coming hours. To conclude, the value of 93 hours with a critical capacity margin is an interesting indicator. However, it needs to be interpreted with care.

Indicator	**Value**	**Reference**
Minimum capacity margin [% of load]	0.0	10
Hours with capacity margin < 0.1 [h]	93	0

Table 9: Reliability indicators for the scenario 'Belgium: high RES share'. The capacity margin drops under 10% mostly in spring in summer, a few hours before large peaks of production from PV panels.

4.1.2 Soft-link: STEP 2

As described in the previous section, the energy system provided by ESTD in the 'Belgium High RES' case does not comply with the adequacy requirement set in this work. The goal is to assess what to ensure the adequacy of the system. This is done through the feedback loop described in section 2.3.

Concretely, the method is split in two parts: (i) a parametric study using Dispa-SET, reducing step by step the electrical demand and (ii) the introduction of new constraints in the ESTD model. Finally, after running the ESTD optimisation, a new energy system is provided. This one is fed to Dispa-SET, and the system adequacy is assessed once again.

Note that for every iteration of the parametric study, the IND *HeatSlack* price has been adjusted so that the total *HeatSlack* productions match in the two models. This follows the methodology described in section 2.2.

Parametric study: electrical EUD reduction

The first task of the feedback loop method is to evaluate the lack in power capacity of the energy system. Link to that, the ultimate goal is to get rid of the lost loads (in other words to have ENS = 0). To do so, the Dispa-SET optimisation is run with different electrical demands, lowered in each run. As soon as the ENS reaches zero, one is able to determine what is the lack of power in the system.

See figure 25 where the ENS is depicted when the electrical demand is multiplied by factor K_{elec} between 1 and 0.85. The figure shows thatt a reduction of 12.5% of the electrical demand ensures the suppression of any lost load in the system. In other words, the initial system suffers from a lack of electrical power of (1/0.875)-1 = 14.3%. This will be translated as a constraint in ESTD, imposing a minimum total capacity of the dispatchable units 14.3% higher than initially installed.

To confirm this, another set of experiments have been carried out with the same system (see details in Appendix D.1.1). For these experiments the power of the dispatchable units is increased, while keeping the initial electrical demand. As a result, the parametric analysis showed that lost loads are completely suppressed for a CCGT power increase between 10% and 20%. This matches with the factor of 14.3% just presented.

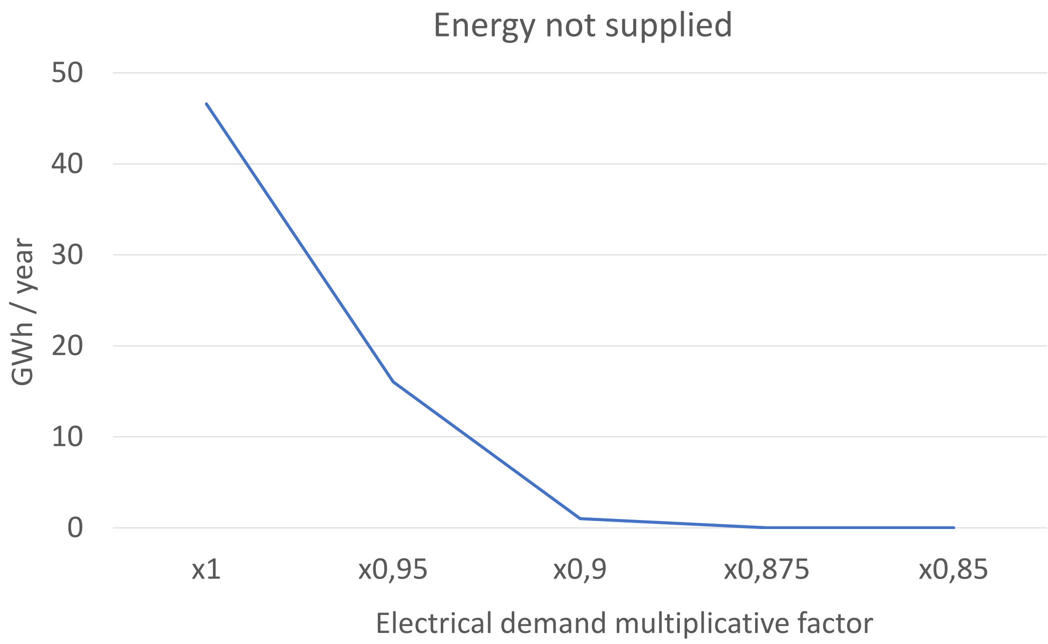

Figure 25: Results from the parametric study on the 'High RES' case. By multiplying the electrical demand by a factor 0.875, the Dispa-SET optimisation results in a system with no lost load (ENS = 0).

Next to that, the second adequacy indicator to improve concerns the load shedding. In that respect, the constraint to add in ESTD is linked to the maximum amount of energy shedded, for the worse period exceeding the established limits. In this case, it represents a period of 88 hours, where 76 GWh are shedded. Then, constraints are implemented in ESTD will ensure that a total of 76 GWh of electricity can be provided either by flexible or by storage units (or both), during 88 hours. Those two quantities correspond to parameters EN_{shed} and Δt_{shed}, as defined in section 2.3.2.

Adequate system

After including in the ESTD model the new constraints, a new energy system results from the ESTD optimisation. This one is referred to as the 'adequate system'. The latter is really close to the initial system, except that a new technology is added: a Gas Turbine (GTUR) unit of 1.65 GW. This technology running on gas is characterised by a relatively low efficiency (43%) but has low installation and maintenance costs (details in Appendix

D.1.2). Therefore, ESTD installs it to cope with issues of load shedding and lost load. In other words, this very flexible unit will be in operation only when a lack of power appears. Still about this adequate system, all the other units have similar installed capacities. Small variations are noticeable but they stay in the range of 2% (e.g. increase of 1.3% of the lithium battery capacity, decrease of 1.9% of the DHN storage capacity). Only the Combined Cycle Gas Turbine (CCGT) power capacity increases by 6.5%. For further details regarding this new system, see Appendix D.1.3.

For the rest of this section, the behavior, adequacy and reliability indicators of the adequate system are presented. Note that for this system, the IND *HeatSlack* price is fixed to 37.65 €/MWh so that its yearly production matches the one in ESTD (37.85 €/MWh in the initial case).

First of all, the main difference concerns the number of start-up of the dispatchable units (see Table 10). First, the number of start-up of the GTUR reaches more than 100. This unit is used mainly to suppress the lost loads that were observed in the initial system. Indeed, the periods when the GTUR produces power corresponds to periods where lost loads happened in the initial system (see Figure 26). Note that this unit produces 100 GWh throughout the year, among which 80 GWh are produced between 9th of February and 12th of February. This corresponds to the exact time slot when lost load appeared in the initial optimisation. The GTUR is then used for its flexibility in the adequate system meaning that the CCGT is less responsible for balancing the variations of production and demand: its number of start-up drops by 46%.

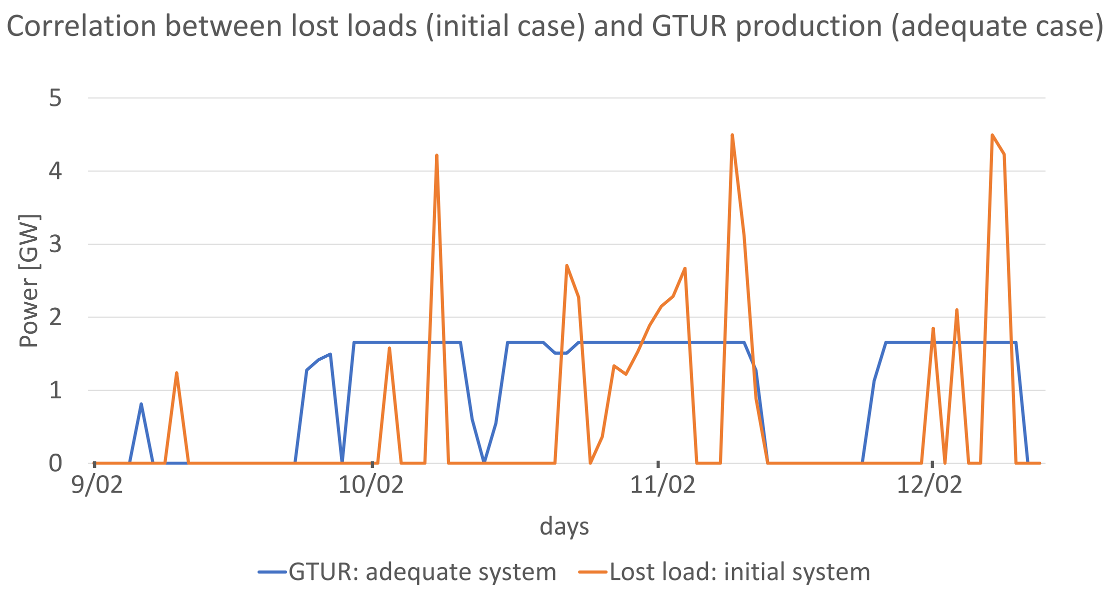

Figure 26: The implementation of a gas turbine (GTUR) solves problems related to adequacy. The production of the latter in the 'adequate' system matches the loss of load occurrences in the 'initial' system.

Another important element to notice is that the numbers of equivalent full discharge cycles diverges for the three short-term storage units. The PHS unit is used more in the adequate system and it delivers in total 10.5% more electricity compared to the initial system. However, the lithium batteries provide 0.6% less electricity compared to the initial system. Remember that the battery capacity changed with the feedback loop process, explaining that the evolution of the number of equivalent cycle is different than the output power evolution. By combining these two storage units, in total the storage output electricity flows are equivalent in the two cases.

As far as the curtailment is concerned, it decreases slightly. Indeed, the total energy curtailed amounts now to 413 GWh/year. This represents only 0.4 % of the yearly RES electricity production, which is a negligible energy loss overall. The decrease in curtailment is linked to the increase of lithium battery capacity, which can then absorb more of the RES production peaks.

The reader should note, some analysis have been carried out on the impact of extra storage capacities on curtailment (see Appendix D.1.1). A quick conclusion of these is that an increase of 40% of the lithium battery capacity reduces the yearly curtailment to 90GWh.

In addition, the operational costs and emissions do not vary so much with the addition of the gas turbine unit. Only small additional costs and emissions are linked to the electricity produced by the GTUR. Regarding the GWP, it represents an increase of 1.36% of the operational $CO_2 - eq$ emissions (+452 $ktCO_2 - eq/year$).

Category	Details	Dispa-SET: initial	Dispa-SET: adequate	Evolution
Start-up [-]	IND COGEN GAS	106	105	- 0.9%
	CCGT	37	20	- 46%
	GTUR	0	109	new
Eq full discharge cycles [/year]	Lithium Battery	200	195	- 2.5%
	PHS	85	94	+ 10.5%
	DEC THMS	250	242	- 3.1%
Curtailment [GWh]	All RES units	450	413	- 8.2%
OPEX [B€/year]	IND COGEN GAS	4.38	4.38	none
	CCGT	1.07	1.07	none
	GTUR	0	0.009	new
CO_2-eq emissions [$ktCO_2$-eq/year]	Wood	n.a.	n.a.	
	Waste	n.a	n.a.	
	Natural Gas	33 272	33 724	+ 1.36%

Table 10: The behaviour indicators in the scenario 'Belgium: high RES share' are represented for 3 simulations: the 'initial' system and 'adequate' systems both ran with Dispa-SET. The 'Evolution' column compares the two Dispa-SET runs. Note: 'OPEX' = resource costs + operational costs'. The addition of the GTUR has negligible effects on the annual budget and $CO_2 - eq$ emissions

Finally, in the adequate system, the DHN storage curve has the same pattern as the initial case, but never reaches its full capacity. The maximum level corresponds to 87.5% of the latter (see Figure 43 in Appendix D.1.3). It seems like the installed capacity is overestimated. To confirm this, the adequate system was modified: the DHN storage capacity was reduced to 87.5% of the initial value. As detailed in Appendix D.1.4, the results of the optimisation are exactly the same. In addition, the reduction of storage capacity leads to savings of almost 20M€/year.

Concerning the indicators of adequacy (Table 11), they are all below the limits established. With the addition of the gas turbine unit, both the ENS and LoLE have been brought to zero. The load shedding indicators are also compliant with the requirements. Again, the GTUR plays here a major role in this improvement.

Concretely, thanks to the improvements made on the power system, this time the admissible hours of load shedding are at the edge of respecting the limits proposed by Elia (see Figure 27). Only four hours exceed the limited established for the 'surplus' category: load shedding < 5.46% of the peak load. Actually, during simulation, 18 hours of load shedding were in the category '2.14% < load shedding < 4.29%', in which only 8 hours are accepted. This is why ten hours of surplus appear. Based on the criteria set in this work, this should not be admissible (see Table 2). However, it is very close to adequacy and this is discussed further in section 5.

Indicator	Value	Limit	Check
Load shedding [GWh]	26	5078	v
Max load shedding power [% peak load]	3.23	5.46	v
Lost of Load Expectancy [h]	0	3	v
Energy not Supplied [GWh]	0	0.2	v

Table 11: Adequacy indicators for the 'adequate system'. All the adequacy requirements are respected thanks to the new constraints applied in EnergyScope TD.

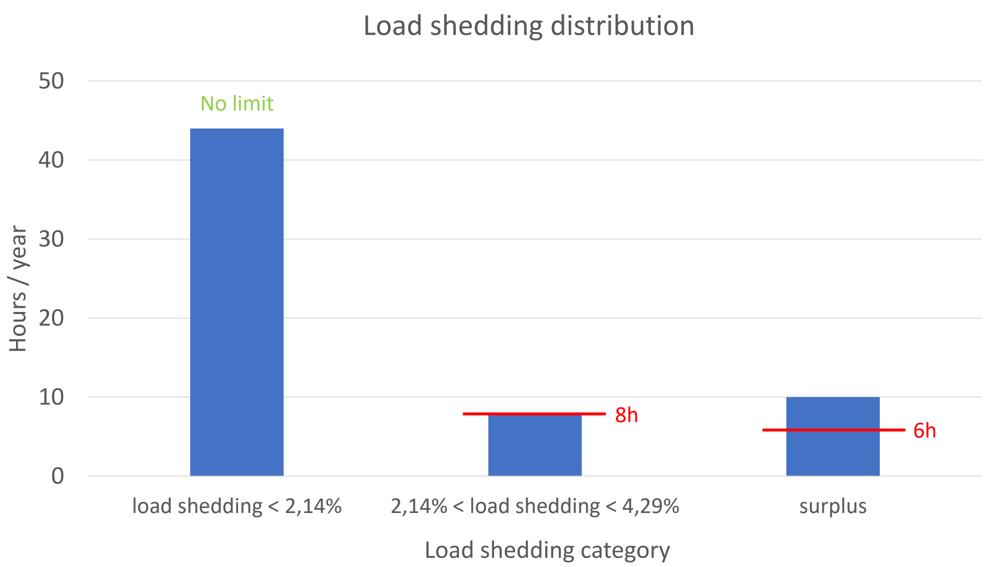

Figure 27: Load shedding levels normalised with the peak load of the 'adequate system'. Since the number of hours in the middle category reaches the limit (8h), the surplus category gathers all the additional hours with load shedding < 5.46%. This surplus of hours exceeds by four hours the limit established (6h).

The last indicators of interest concern the reliability of the power system. As detailed in Table 12, the minimum capacity margin remains 0.0%. However, during only 25 hours the capacity margin drops below 10%. This is a strong improvement compared to the initial case. The cause of this is obviously the increase of the combined cycle (CCGT) power capacity and the implementation of the gas turbine (GTUR).

Indicator	Value	Reference
Minimum capacity margin [% of load]	0.0	10
Hours with capacity margin < 0.1 [h]	25	0

Table 12: Reliability indicators for the 'adequate system'. The number of hours where the capacity margin drop below 10% decreased by 68 hours.

Finally, ensuring the adequacy and reliability of a power system requires additional economical resources. In the case of the adequate system presented in this section, the yearly supplementary costs amount to 98 M€, among which more than the half is linked to installation of new units (see Figure 28). Compared to the total costs of the initial energy system (28.7 B€/year), these 98 M€ represent a yearly budget increase of 0.34%.

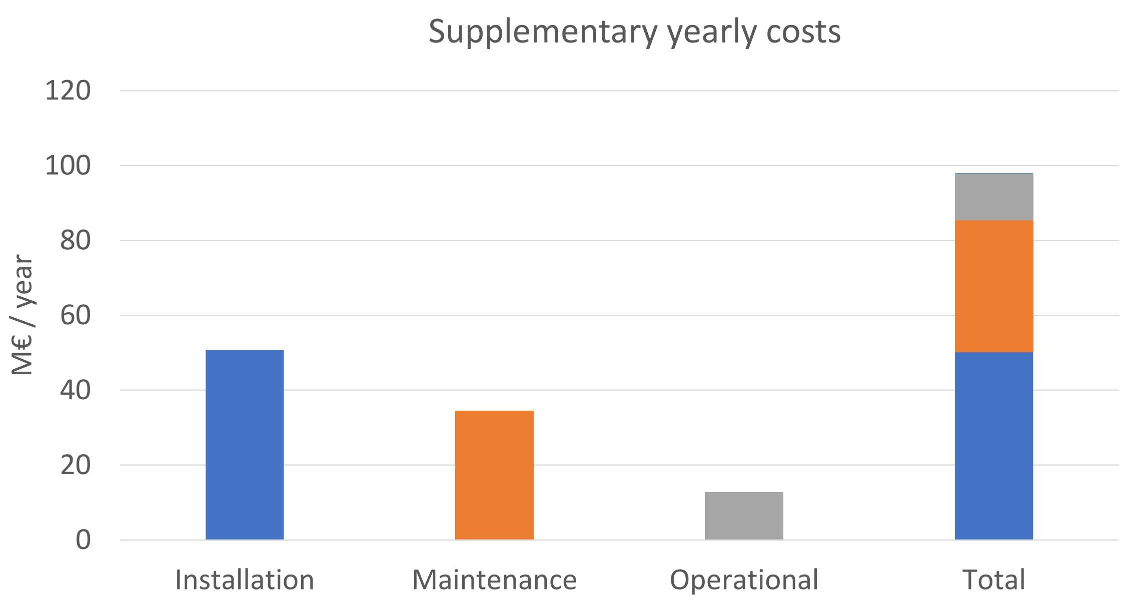

Figure 28: Economical comparison of the 'adequate' system with the 'initial' system: the extra costs are represented here. 'Operational' only represents the differences between Dispa-SET simulations.

On this previous chart, the increase in the installation cost is linked to the installation of the GTUR (45 M€) and additional lithium battery capacity (13 M€). On top of that, 18 M€ are invested in increasing the CCGT power capacity as well. However, almost 20 M€ are saved thanks to the reduction of the DHN storage and production capacity.

4.2 Belgium: energy mix

In this second Belgian case, multiple technologies are implemented, involving RES, nuclear and fossil fuels. Electrical imports also contribute to balancing the electricity layer. A capacity of 9GW of interconnection lines is considered. This will have a positive impact on the adequacy of the system, as described further in this section.

Compared to the 'High RES share' case, this 'energy mix' case may be slightly closer to the reality, because allowing interactions with other countries, and relying on different types of technologies.

The soft-link methodology was applied on this study case, including adequacy assessment of an initial system, parametric analysis in Dispa-SET and feedback loop on ESTD. All this is described in the rest of this section.

4.2.1 Soft-link: STEP 1

As a reminder, the first step of the soft-link consists in analysing the results of the two optimisation. The goal is to determine if the energy system provided by ESTD is adequate.

Productions analysis

First and foremost, the analysis of this study case starts with a comparison between the yearly productions of units in the two models. The yearly electricity productions are depicted in Figure 29 for the two models. The first thing to notice is that our model of the electricity imports in Dispa-SET gives similar results than the one in EnergyScope TD: the electrical imports are close to 10 TWh/year for the two optimisations.

Next to that, an important difference in production concerns the geothermal and nuclear units. Those two units seem to balance each other (the nuclear has a lower production, and geothermal a higher production in Dispa-SET). To understand those mismatches, one has to know that an outage factor is introduced in ESTD, limiting the yearly production of the nuclear and geothermal units. This factor is set at 85%, meaning that the units can not produce more energy than 0.85*8760h times the installed capacity. However, the unit can still deliver its maximum power at some point. In Dispa-SET, no such constraint on the total production is implemented. As a direct consequence, the geothermal energy being free, Dispa-SET uses this technology at full power all year long and makes the nuclear power vary, to absorb variations. In the contrary, ESTD keeps a constant nuclear power (85% of the nominal power) and adjust from time to time the power delivered by the geothermal unit.

About the RES units (on the right side of Figure 29), one can notice small production differences for the three units. This is actually linked to a higher curtailment in Dispa-SET (more details in the next section: Behavior indicators).

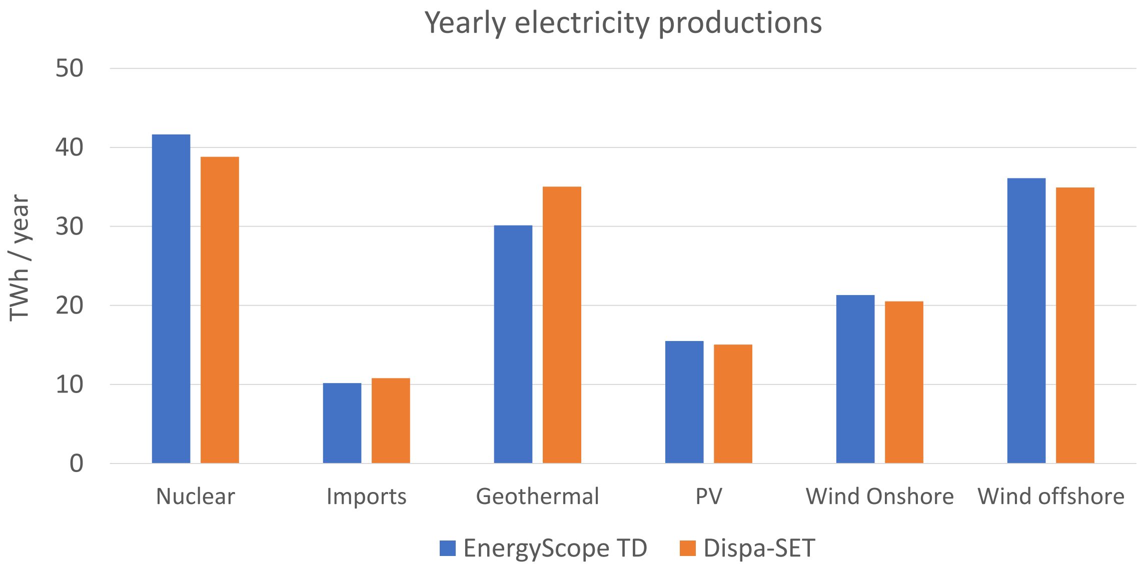

Figure 29: Electricity production per unit comparison between EnergyScope and Dispa-SET for the scenario 'Mix'. The geothermal yearly production is limited in ESTD, not in Dispa-SET: this explains the greater production in the latter. As a consequence, the nuclear unit produces more in ESTD. Curtailement is greater in Dispa-SET, due to higher technical resolution, explaining the RES production differences.

Regarding the heat generation units (Figure 30), the IND heat productions are slightly different in the two models. In this study case, although the IND *HeatSlack* prices are equal in the two models, Dispa-SET uses these units less. This gap is compensated by the IND electrical resistance. The electricity is supplied via the excess of production of the geothermal electricity production unit.

About the LT heat production, a mismatch appears in the DHN layer. Two technologies can produce DHN heat: a heat pump (5.45GW) and a geothermal unit (4GW, which corresponds to the DHN *HeatSlack*). This time, the *HeatSlack* price was adjusted in Dispa-SET so that its yearly production does not exceed the production of the 8760h * 4GW. In EnergyScope TD, an outage factor of 0.85 is applied on the geothermal unit. This pushes the heat pump to fill the gap. In Dispa-SET, the outage factor is not applied on the *HeatSlack*, and this results in a higher production of the latter. This explains the difference in DHN heat production of the heat pumps in the two models.

Finally, the DEC heat pump being the only DEC heat production unit, productions are similar in the two models.

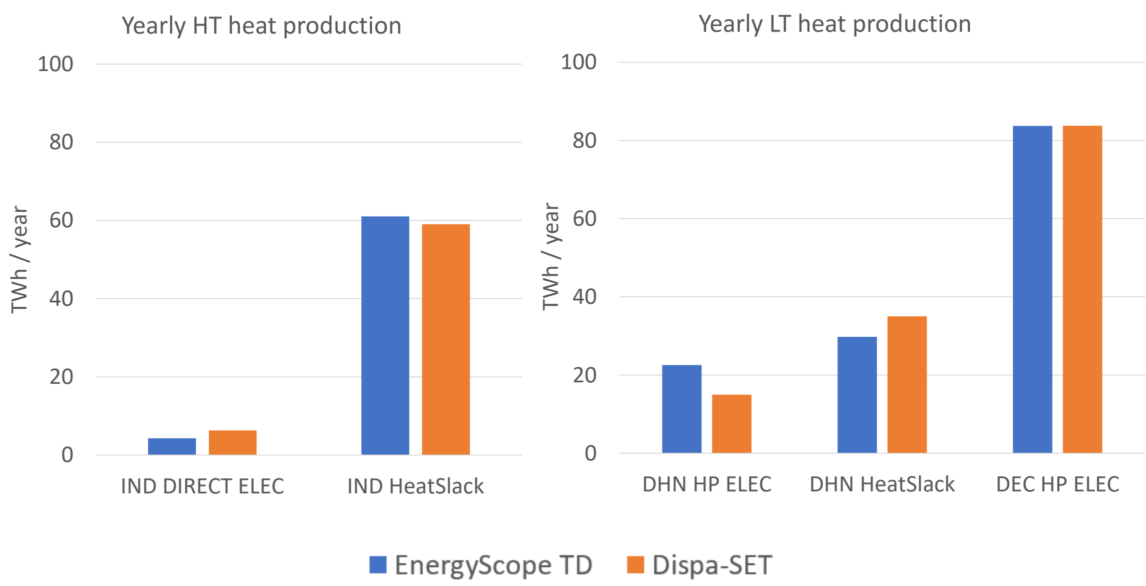

Figure 30: Heat production per unit comparison: case 'Belgium: energy mix'. The DHN *HeatSlack* yearly production is limited to 85% in ESTD, not in Dispa-SET. This induces a production gap for both the DHN heat pumps and DHN *HeatSlack*.

Behavior indicators

The analysis of the behavior indicators in this study case shows a lot of similarities between the two models. Some figures illustrate this statement in Table 13.

First of all, as explained earlier, the nuclear unit produces electricity without interruption in ESTD. So, its number of start-up is one. For the geothermal unit, this is the other way round. A lot of variations occur throughout the year, inducing more than 100 start-ups. As far as the geothermal unit in Dispa-SET is concerned, it produces during the whole year at full power. Finally, although the number of start-ups of the nuclear unit in Dispa-SET is low, its production fluctuates a over the year.

After that, unlike in the 'high RES share' case, the number of equivalent full discharge cycles of the PHS unit are similar in this study case. A reason explaining that observation is the low storage capacity of the system. The PHS can not absorb more RES peaks than what ESTD plans. These variations might be absorbed by the the DEC THMS unit, as it has a higher number of equivalent full discharge cycles in Dispa-SET(+ 17.5%).

The curtailment in Dispa-SET reaches more than 2.4TWh in this case (2.8% of the total RES production). Where in ESTD, this value is only 0.38 GWh. Two elements may justify this important gap. Firstly, in ESTD around 17GWh of Battery Electric Vehicle (BEV) are installed, and these are not taken into account in the soft-link. Secondly, the use of typical days in ESTD may misrepresent the highest RES production peaks and consequently underestimate the curtailment.

On the economical aspects, the OPEX of the two models are similar. The increase correspond to the production difference, which are minor. Indeed, for the nuclear unit, the extra operational costs (OPEX minus resource cost) represent 2.3% of the yearly total operational costs.

Finally, the majority of the CO_2 emissions is due to the *Heatslack* units. The latter comprehends to boilers (running on waste, coal and natural gas). This represents 86% of the operational Global Warming Potential (GWP) and 76% of the total GWP (including construction of the plants, etc). This latter amounts to $44MtCO_2 - eq/year$ in this initial 'energy mix' case. As far as the uranium and electricity imports are concerned, their emissions are proportional to their respective use. The energy supplied by both technologies being similar in the two models, we can say that the emissions are similar as well.

Category	**Details**	**ESTD**	**Dispa-SET**
Start-up [-]	NUCLEAR	1	3
	GEOTHERMAL	105	1
Eq full discharge cycles [/year]	Pumped hydro storage	161	164
	DEC THMS	308	362
Curtailment [GWh]	All RES units	0.381	2 431
OPEX [M€/year]	NUCLEAR	436	418
	Imports	858	910
CO_2-eq emissions [$ktCO_2$-eq/year]	Wood	97	n.a.
	Waste	1 400	n.a.
	Coal	13 389	n.a.
	Natural Gas	18 670	n.a.
	Uranium	439	409
	Imports	4 904	5 200

Table 13: Behavior indicators for the scenario 'Belgium: energy mix'. The main behavior difference concerns the level of curtailment, much higher in the Dispa-SET simulation.

Adequacy indicators

Globally, the adequacy of this 'energy mix' case is good. Indeed, as described in Table 14, only the Energy Not Supplied (ENS) exceeds the limit established. The value of 3.07 GWh of ENS is far below the equivalent value of the precedent study case (46 GWh), proving that the adequacy of this initial energy system is better. Similarly, the lost loads only occur during 3 hours here.

Regarding load shedding, it follows the same trend: 20 GWh are shedded in this scenario, which can be compared with 110 GWh in the 'high RES case'. How can we explain this ? It is linked to the important amount of constant electricity supplied to system: nuclear, geothermal and imports. Together, they can ensure a constant base production of 18.6 GW. With the peak electrical load being roughly 17 GW (taking into account losses, electro-mobility, electrolysis, etc), most of the time the system is able to answer the demand. In addition, the system comprehends large installed capacities of RES, making the electrification of the heat sector convenient through the Thermal Storage (THMS).

Indicator	Value	Limit	Check
Load shedding [GWh]	20.0	5078	v
Max load shedding power [% peak load]	3.14	5.46	v
Lost of Load Expectancy [h]	3	3	v
Energy not Supplied [GWh]	3.07	0.2	x

Table 14: Adequacy indicators for the scenario 'Mix'. Only the ENS does not meet the adequacy requirements.

Nevertheless, 2.9 GWh exceed the established ENS limit. Next to that, the load shedding distribution does not meet the requirements neither. As illustrated in Figure 31, 23 hours of load shedding occur at a level between 2.14 and 4.29% of the peak load, where 8 hours are accepted.

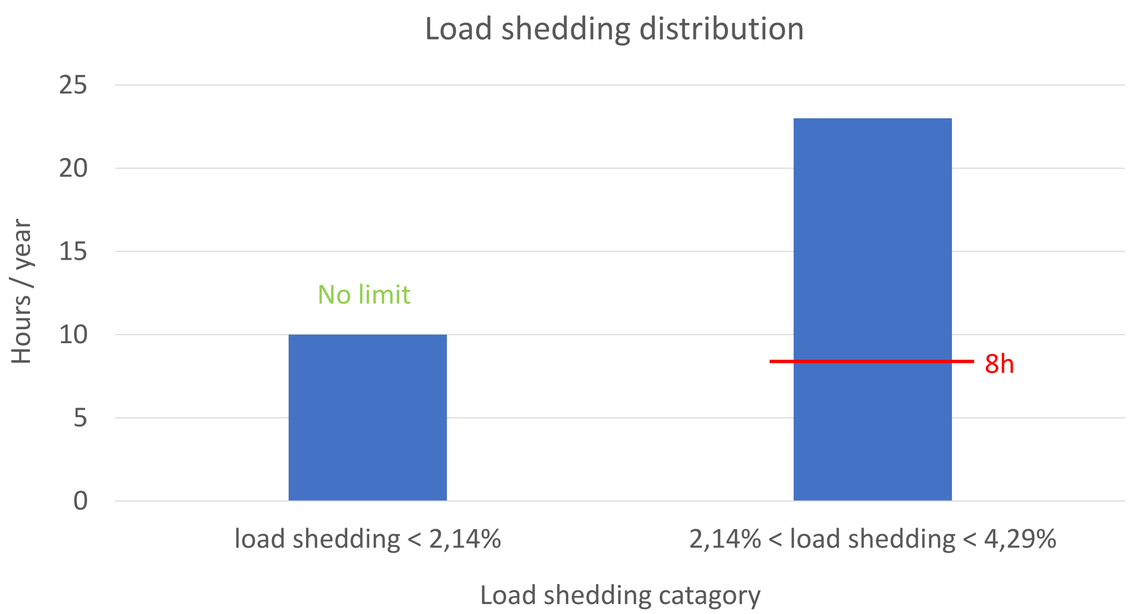

Figure 31: Number of hours of load shedding, per category of demand response as specified in Elia's report [16]. The adequacy criteria are not met. for the category '2.14% < load shedding < 4.29%' exceeds the established limit (8h).

Reliability indicators

The reliability of the system is also assessed: for 163 hours of the year (roughly 2% of the studied period) the capacity margin is lower than 10% (see Table 15). Unlike in the 'high RES share' case, here the capacity margin is critical only during winter. In the previous case, the capacity margin decreased under 10% a few hours before solar peaks in the summer: the system could fill up its storage within the same optimization horizon which explains the drop in capacity margin. Here this is not the case. This points toward a lack of dispatchable power in the system.

Indicator	Value	Reference
Minimum capacity margin [% of load]	0.0	10
Hours with capacity margin < 0.1 [h]	163	0

Table 15: Reliability indicators for the scenario 'Mix'. The capacity margin drops below 10% for roughly 2% of the year. This is probably due to the lack of electrical storage in the considered system.

4.2.2 Soft-link: STEP 2

Following the methodology presented in 2.3, this second step is divided in two parts: (i) run a parametric study (on the electrical demand) in Dispa-SET, (ii) adding new constraints in EnergyScope TD. Then the models are ran again to check that the new system meets the adequacy requirements.

Electrical demand reduction

In Figure 32, the evolution of the ENS is depicted, as function of the electrical demand in Dispa-SET. With 0.95 of the electrical demand, the ENS reaches 0. Therefore, the system seems to suffer from a lack of electrical power installed of roughly $1/0.95 - 1 = 5.26\%$. This is taken into account in a first constraint in the ESTD model, through the factor K_{elec} (see section 2.3.2).

Still following the soft-link methodology, another constraint will be included in ESTD. The goal here is to ensure a storage reserve margin. The largest load shedding period lasts for 15 hours in this case, with a total energy shed of 12.29 GWh. These correspond to parameters Δt_{shed} and EN_{shed} respectively. Both define the second constraint added to the ESOM (as defined in section 2.3.2).

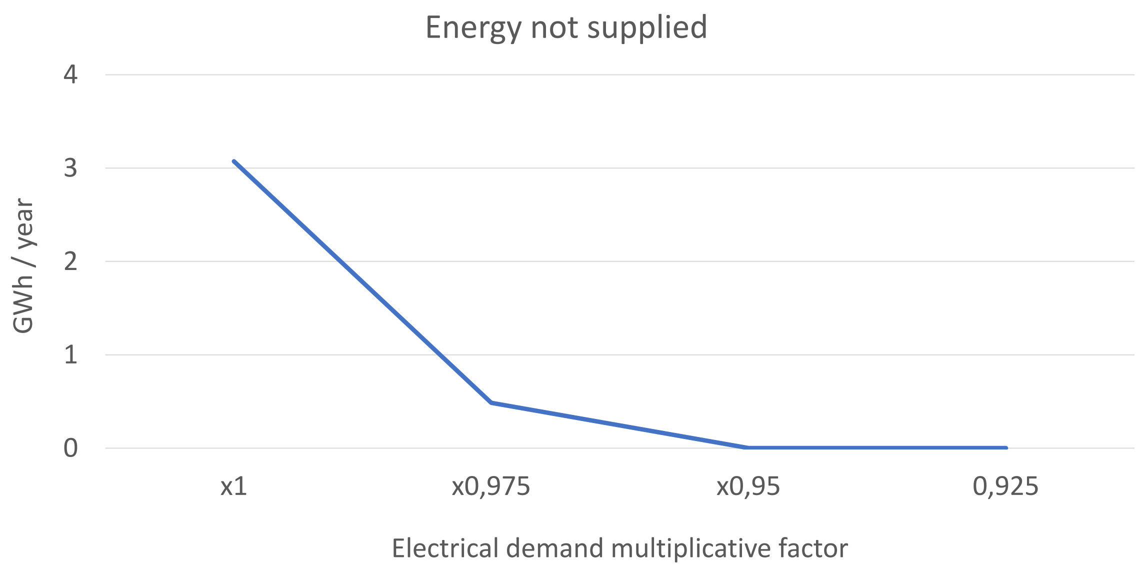

Figure 32: Results from the parametric study on the 'Mix' scenario. By multiplying the electrical demand by a factor 0.95, the Dispa-SET optimisation results in a system without any lost load (ENS = 0).

Adequate system

After adding in ESTD the constraints described above, a new energy system is provided. The modifications made to the system are the following: (i) a new Combined Cycle Gas Turbine (CCGT) of 0.82GW is installed, (ii) 8.5 % less PV are installed, (iii) the DEC heat storage capacity is increased by 10% and (iv) the DHN storage capacity is decreased by 2.6% . All other variations are negligible (less than 2%).

The addition of the CCGT has the biggest impact on the system. Among others, one consequence is a reduction of 23% of the electrical imports, due to the CCGT production. Details regarding installed capacities and productions are provided in Appendix D.2.1. For the rest of this section, this energy system will be referred to as 'adequate system'.

The analysis of this new system starts with the behavior indicators (see Table 16). First of all, the numbers of start-ups of the nuclear and geothermal units are identical to the initial case. Notice that the CCGT is used for more than coping with peak loads and solving problems of adequacy: in total, the energy produced by this unit corresponds to around 35% of its maximum yearly production. This results in 114 start-ups over the year.

The storage management (equivalent full discharge cycles) and curtailment quantities do not changed compared to the initial system. The small reduction in curtailment may be linked to a higher use of the DEC storage unit (for which the capacity is slightly increased). Indeed, although the number of equivalent full discharge cycles of the DEC THMS is lower in the adequate case, the total DEC output heat flow is 5% higher in this case.

About the economical aspects, the OPEX of the nuclear unit remains unchanged. On the other hand, the costs linked to electricity imports diminish, highlighting a decrease of 23% of the energy imported. The reason for this is that using the CCGT running on gas (41 €/MWh) with high efficiency (62.5%) is cheaper than importing electricity (84€/MWh)

Nevertheless, importations of electricity still represent more than 8TWh (5% of the total electricity production). This is because the CCGT is limited in power (0.82GW), hence interconnections lines are used to supply greater loads.

Finally, the yearly $CO_2 - eq$ emissions are lower in the adequate system. This is linked to the increased use of the CCGT and the decrease in electricity importations. This result requires some explanations: we assume that the European electricity imported in Belgium has a Global Warming Potential (GWP) of 0.48 $ktCO_2 - eq/GWh$. In comparison, the equivalent value for the gas is 0.267. Then, for each GWh of electricity produced by the CCGT, $0.43ktCO_2 - eq$ are emitted, which is lower than for the imports. In the future, the European grid is expected to become cleaner, which could alter these results.

In hte previous paragraph, we compared emissions between the 'initial' and 'adequate' runs in Dispa-SET. Recall that the dispatch (hence the $CO_2 - eq$ emissions) is different in ESTD and Dispa-SET. If we consider the ESTD dispatch, the total yearly $CO_2 - eq$ emissions increase by 317 kt between adequate and initial case (+ 0.7% compared to the total GWP of the initial system).

Category	Details	Dispa-SET: initial	Dispa-SET: adequate	Evolution
Start-up [-]	NUCLEAR	3	3	
	GEOTHERMAL	1	1	
	CCGT	/	114	
Eq full discharge cycles [/year]	PHS	164	148	- 9.7%
	DEC THMS	362	346	- 4.4%
Curtailment [GWh]	All RES units	2431	2 337	- 3.9%
OPEX [B€/year]	NUCLEAR	418	418	
	Imports	910	697	- 23 %
	CCGT	/	187	
CO_2-eq emissions [$ktCO_2$-eq/year]	Natural Gas (CCGT)	/	951	
	Uranium	409	408	- 0.2%
	Imports	5200	3984	- 23%

Table 16: The behaviour indicators in the scenario 'Mix' are represented for 3simulations: the 'initial' system ran with (i) EnergyScope TD, (ii) Dispa-SET and (iii) the'adequate' system in Dispa-SET. The 'Evolution' column compares the two Dispa-SETruns. Note: 'OPEX' = resource costs + operational costs' The operational expenditures are lower in the 'adequate' system as it relies on gas rather than electricity imports.

The adequacy of the system is improved by the addition of the addition of a Combined Cycle Gas Turbine (CCGT) (0.82GW). As depicted in Table 17, the four indicators presented meet the established limits. Especially, in this adequate system, the value of 3.8 GWh of load shedding is very low. As a comparison, in the adequate system of the case 'high RES share', still 13.4 GWh of load shedding were observed. Also, the ENS reaches now zero, which was the objective.

Indicator	Value	Limit	Check
Load shedding [GWh]	3.8	5078	v
Max load shedding power [% peak load]	3.12	5.46	v
Lost of Load Expectancy [h]	0	3	v
Energy not Supplied [GWh]	0	0.2	v

Table 17: Adequacy indicators for the 'adequate system' in the 'Mix' scenario. All the adequacy criteria are respected.

By pushing the analysis further, in Figure 33 is depicted the distribution of load shedding, depending on its normalised value. As expected with the result just presented, the number of hours for each category comply with requirements.

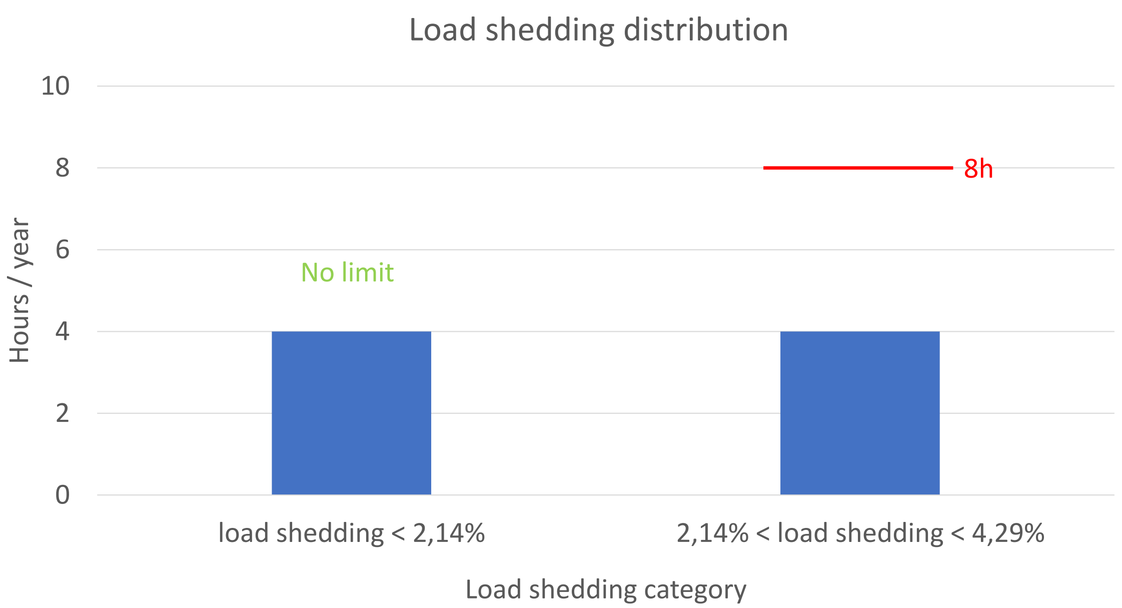

Figure 33: Load shedding levels normalised with the peak load of the 'adequate system'. The adequacy criteria are respected.

The last indicators, giving insights on the reliability of this adequate system, are present in Table 12. Compared to the initial system, the number of hours with a capacity margin below 10% is lower here: 117h. These happen mostly in winter. As in the initial system, this adequate system presents a low capacity margin. This may be explained by the lack of electrical storage capacity of the system. The latter would increase the capacity margin (according to the definition set in this work).

Anyway, the system is at risk during only 1.3% of the time, which seems reasonable. On top of that, in this soft-link, the capacity margin is only assessed by looking at the power system. In ESTD, this scenario implements production of renewable fuels (a flexible load) and Battery Electric Vehicle (BEV) (both a flexible load and electrical storage). These are not represented in this soft-link. Further works could take these into account to give a more accurate representation of the system reliability.

Indicator	**Value**	**Reference**
Minimum capacity margin [% of load]	0.0	10
Hours with capacity margin $<$ 0.1 [h]	117	0

Table 18: Reliability indicators of 'adequate system' in the 'Mix' scenario. The number of hours here the capacity margin drops below 10% is decreases by 46 hours. Again, this might be difficult to reduce further without electrical storage (with the definition of capacity margin presented in this work)

Finally, one could wonder what is the impact of all the system modifications on the total cost? The answer is presented in Figure 34. Surprisingly, the total yearly costs decrease with the introduction of the constraints in the ESTD model. To interpret this results, several elements need to be clarified: (i) the installation costs are lower in the adequate system. In spite of the new CCGT installation (+ 30M€/year), the PV capacity is reduced which results in 50M€/year in savings. (ii) The operational cost difference depicted in the figure comes from the Dispa-SET simulations only (recall, a part of the electricity initially provided by imports is now produced by a CCGT, at lower cost). (iii) Looking only at the ESTD simulations, there is an extra total cost of 3 M€/year between adequate and initial systems. This is expected, since ESTD minimises the cost of the system. And a system with less constraints is expected to be cheaper. The total cost of the system amounts to around 18.5 B€/year.

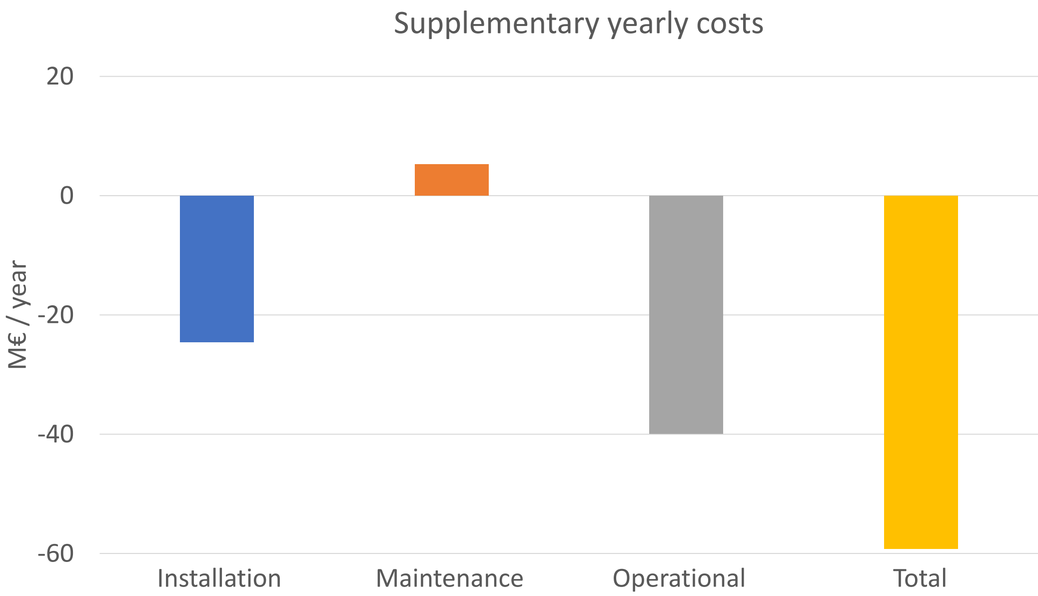

Figure 34: The extra cost of the 'adequate' system, compared to 'initial' one. The adequate system is cheaper than the initial one, when we consider the dispatch (and operational costs) of Dispa-SET. The savings in the installation costs comes from a decrease in the PV capacity, which results in a lower RES part in the energy mix.

5 Discussion

The aim of this section is to take a step back regarding the results presented above, and try to extract key messages from each case study. The simulations help challenge the methodology and highlight opportunities of improvements. In that respect, some recommendations are proposed at the end of the section. These gather ideas for improving the soft-link itself, or interesting cases that would be worth investigating in future work.

5.1 'Belgium: high RES share' case

In this case study, the energy system initially provided by ESTD does not comply with the adequacy requirements (ENS, load shedding). Also, note that the energy curtailed through the year (450 GWh) is greater than the total energy shedded (110 GWh) in the Dispa-SET simulation. This results hints that (i) EnergyScope TD plans well the annual energy production needed to supply the demand, and (ii) the needs to soft-link ESOMs with models who has greater temporal resolution to capture variations of production on smaller time scales.

According to our methodology, there is a lack of power capacity of around 2GW. The initial energy system is modified to comply with the adequacy requirements through the addition of constraints described in section 2.3.2. The main modifications are: (i) the addition of a new gas turbine unit (1.65 GW), (ii) an increase of lithium battery capacity (+1.3%) and (iii) an increase of the CCGT power capacity (+ 6.5%). Note that the new system induces a surplus of 450 $ktCO_2 - eq$ per year (0.6% of the total GWP). By observing these variations, it seems the initial system suffers rather from a lack of power capacity than storage capacity. Anyway, thanks to the methodology developed, the new energy system provided by ESTD results in a compromise between an increase of the power capacity and an increase of the electrical storage capacity.

In the description og results, it appears that the system is not fully adequate. Indeed, four hours of load shedding are exceeding the limit established. Nevertheless, to put this result into perspective, one has to know that P2G (e.g. H_2 electrolysis and Synthetic Liquid Fuel (SLF) storage) and P2M (e.g. Battery Electric Vehicle (BEV)), present in the 'initial' ESTD system, are not taking into account in the soft-link. By including those elements in the soft-link, it would certainly improve the adequacy of the initial and final systems. This is why the so called 'adequate system' is well considered as adequate. In reality, those only four hours of extra load shedding could be handled thanks to flexible loads (e.g. BEVs) or by increasing the load shedding price.

Similarly, another remark concerns the DEC and DHN heat pumps: they are intensively used in this energy system to absorb RES peaks by storing heat. Those units certainly improve the flexibility of the system, but the indicators defined in this work can not assess this. For these reasons, the results have to be considered with care.

Finally, in terms of economics, these system improvements represent an increase of 0.34% of the yearly budget (+ 98 M€/year). This allows to supply an extra 131 GWh of demand, suppressing the ENS and 76% of the energy initially shedded. The *Cost_of_Adequacy* KPI amounts therefore to 748 €/MWh. This is in the order of magnitude of the load shedding price set in this work (1000 €/MWh). However, to cope with a lack of power, modifying the system seems more profitable (economically speaking) than the load shedding.

However, the load shedding price may fluctuate, which leads to another interesting conclusion: in future system, the load shedding could have an important role to play in balancing production and consumption, and in adding flexibility to the system. The results of this study raises a question concerning load shedding: could it be economically beneficial to increase the financial budget and soften requirements associated with load shedding, rather than investing more money in the energy system?

In reality demand response is more complex for two reasons: (i) the price is not constant for all contractors and (ii) the demand might not be reduced but shifted (as contractors are required to shed a load at a given moment but could consume at another moment). Further works would be beneficial for representing realistically this complex concept and interpreting economical results.

5.2 'Belgium: energy mix' case

In this second study, the adequacy of initial system is better than in the 'High RES share' case. Indeed, the load shedding is at the edge of the limit in terms of hours distribution, and the ENS exceeds the limit by 3 GWh only. Recall that this scenario considers 8 GW of geothermal units (for electricity and DHN heat production), 5.6 GW of nuclear units and allows for electricity imports up to 9GW. In addition, the offshore wind power capacity is up to 10 GW. Those elements give a system which is close to adequate, even with a lack of electrical storage. However, capacity margin showed that the system is at risk during more than 150h in winter. In this regard, it is important to note that in the ESTD system, 16.7 GWh of BEV are installed. These are not taken into account in the soft-link. Their implementation would improve the capacity margin and lower the level of curtailment. The latter amounts to 3% of the total RES production in Dispa-SET, and less than 1% in ESTD.

The feedback loop process was applied in order to resolve issues with lost loads. The 'adequate' system is very close to the initial one: a new CCGT unit (0.82GW) is implemented, and the PV power capacity is reduced (-8.5%). As expected, the new system meets the requirements of adequacy. This confirms the robustness of the feedback methodology in the two case studies.

Regarding economics, recall that the 'adequate' system has supplementary costs amounting to 3.7M€/year in ESTD simulations. This represents only 0.02% of the annual budget. The dispatch is done differently in the two models, resulting in different total costs. If we consider ESTD operational costs, they are balanced by savings linked to the reduction of the PV capacity. But if we consider the Dispa-SET operational costs, the total balance becomes negative. This is because for the adequate system, Dispa-SET relies more on the CCGT to generate power rather than importing electricity. The electricity produced by the CCGT is indeed more attractive economically speaking. As a result, the extra gas consumed amounts to 178 M€/year, whilst we save 212 M€/year in electricity imports.

To conclude, the reader must be careful when interpreting those results. First, the economical analysis is here dependent on the import cost. In future systems, one could imagine contracts between countries for lowering the import price which would affect the results. Second, the emissions of the new system increase by 317 $ktCO_2 - eq/year$. In our simulations, there are no prices associated with $CO_2 - eq$ emissions. In the future, expensive taxes appearing on GHG emissions may influence the results considerably.

5.3 For future work

In this section, the authors present ideas to improve the soft-link and suggestion for future case studies. Some of them are described in details in Appendix F.

We believe the first step to enhance the soft-link would be to include other sectors and cross-sectoral interaction. For the moment, the methodology focuses on electricity and heat. P2G and P2M are considered only through additional electrical loads. Including these (as well as mobility-to-power and gas-to-power) would paint a more accurate picture of the adequacy of power system and use the wide scope of ESTD.

In addition, the soft-link could be improved via further modifications of Dispa-SET. Our idea would be to add constraints regarding the yearly production of any unit, and limit the availability of each resource. This would solve two problems encountered in this work: (i) the necessity to increase the *HeatSlack* price, if its production exceeds the resource availability and (ii) the impossibility to take into account the outage factors present in ESTD (example in the case 'Belgium: energy mix').

Next, as briefly explained in the discussion of the case 'Belgium: high RES share', P2H technologies are expected to become essential in future systems. Electrification of the heat sector provides flexibility to the system at an affordable cost when linked to Thermal Storage (THMS) (compared to lithium batteries, for instance). However, the indicators defined in this work are not suitable for assessing the benefits of thermal storage. Future work could aim at including the heat in the capacity margin for instance, or distinguishing electrical and heat load shedding, etc. Equally we could consider in the capacity margin other cross-sectoral interactions which would improve the adequacy of the system (P2M, P2G).

Linked to the adequacy indicators, the limits of compliance were established based on current standards (for the ENS and LoLE) and projections for the load shedding. Adequacy is likely to become more and more critical in future power systems. As a result, new requirements will be introduced by TSOs. For this reason, we suggest that the upper limits of the indicators be regularly updated, to ensure to the most relevant assessment of results.

In addition, in the first case study, the cost of adequacy was higher than the load shedding price (1000€/MWh). The latter is an average of the prices found in Elia's report [16]. As this price was arbitrarily set, a parametric analysis of this price could improve soft-link methodology, to put into perspective conclusions on load shedding and the cost of adequacy.

For a future work, the authors suggest applying this soft-link methodology to a multi-cell system (for instance with several countries). New versions of ESTD[11] and Dispa-SET[12] implement the exchange of resources between zones. The tools to process the data of multiple countries have already been developped to carry out the soft-link with a multi-cell case [7].

[11] Multi-cell version of EnergyScope TD on Github: [17]

[12] in development

6 Conclusion

We developed a bi-directional soft-link between an long-term Energy System Optimisation Model (ESOM) and an Unit Commitment and Economic Dispatch (UCED) model. The former (EnergyScope Typical Days (ESTD)) outputs an energy system with cross-sectoral interactions (electricity, heat, gas and mobility). The UCED model (Dispa-SET) optimises the economical dispatch of the units implemented in the energy system in question. The soft-link takes advantage of the high temporal and technical resolution of Dispa-SET to give information on the adequacy and reliability of the power system. Then, based on this information, a feedback loop is applied to EnergyScope TD to ensure an adequate and reliable energy system. Note that the methodology is valid for single or multi cell systems.

The methodology presented has several advantages. First of all, the data transfer between ESTD and Dispa-SET realistically represents the electricity and heating sectors, as well as interactions between these two. Including the heat sector in the soft-link is essential for studying energy systems, since it is responsible for an important part of the primary energy consumed in Europe.

Next to that, the soft-link can be applied to complex systems, including RES technologies, storage units, etc. The methodology is automatic and easy to use. It does not require an in-depth analysis of the Dispa-SET results to add constraints to ESTD. This would be difficult in the case of complex systems (e.g. with cross-sectoral interactions, storage units, etc).

The soft-link methodology presented is composed of several steps. The first one consists in transferring and processing information between the two models. This has been thoroughly explained in section 2.3.1. This transfer was carried out in a coherent way with minimum loss of information via careful comparison of the two models.

We defined indicators to analyse the outputs of the two models. These indicators can fall in one of the following categories: (i) Behaviour, (ii) Adequacy, and (iii) Reliability. The next paragraph sum up findings related to these indicators. All the conclusions come from our two case studies: (i) an islanded Belgian energy system with high RES share and (ii) a scenario with a mix of technologies which could enable a Belgian energy transition.

The behaviour indicators highlight differences between the two models. Due to the low temporal and technical resolution, ESTD underestimates the curtailment (1% of RES production in ESTD against 3% in Dispa-SET). Apart from the curtailment the other behaviour indicators have similar values in the two models: ESTD estimates well the yearly power production per unit, the use of resources and hence total $CO_2 - eq$ emissions.

The second category aims at assessing the adequacy of the power system. Here, adequacy refers to balancing electrical production and consumption, plus ensuring a tertiary reserve. In this work, every system outputted by ESTD did not comply with our adequacy requirements: lost loads were observed (indicating a lack of power capacity). The lack of power capacity was estimated at 5% in one scenario ('Mix'), and 15% in the other ('High RES'). And the lack of storage reserve capacity, was estimated.

The next step of the soft-link concerns the feedback loop applied to EnergyScope Typical Days (ESTD). In this step, a parametric study is applied to Dispa-SET to assess the lack of power capacity quantified by a parameter (K_{elec}). The lack of storage capacity is quantified via the largest amount of energy shedded (En_{shed}) in a continuous period of time (Δt_{shed}). All of these quantities define new constraints to apply to ESTD. Note that these constraints allow the model to decide how to comply with the new requirements.

Once the methodology was applied, the modified energy system complied with all of the adequacy requirements. However, after applying the feedback loop to ESTD, additional dispatchable power capacities are added to the systems (respectively 2GW and 0.82 GW for the first and second study cases). Interestingly, only few modifications of the storage capacities are observed (less than 10%). This emphasises a lack of power of the system initially proposed, rather than a lack of flexibility. Eventually, the new energy systems do meet adequacy requirements. In both cases, the annual budget increases by less than 1% to reach full adequacy. On the economics, modifications made the the energy system increased the annual budget by less than 1% in one case ('High RES') and negative in the other (meaning we saved money compared to the investment and operation of the 'initial' system).

The case studies outline some limits of the soft-link methodology. The most notable one concerns the fact that only heat and electricity are thoroughly handled in the soft-link. Other sectors such as mobility, gas management, are only partially present in this soft-link. To a certain degree, this lowers the flexibility of the energy system and hence its adequacy.

Then, another limitation is linked to the *HeatSlack*. The latter is an aggregate of all the heat-producing units that are not CHP unit or power-to-heat units. A problem is that the user needs to check manually that the *HeatSlack* production does not exceed the resource availability. If this is the case, the *HeatSlack* price needs to be adapted which slows down the whole soft-link process.

Finally, the feedback loop applied to EnergyScope TD is based on indicators for which margins have been arbitrarily chosen. The problem is that no formal framework is established for assessing the adequacy of power systems. As a result, the process relies on actual standards and projections made by Elia. Those are likely to evolve in the coming decades with growing cross-sectoral interactions.

Potentially there is room for further research and work in this area, both to improve the soft-link itself, or to investigate other case studies. A non-exhaustive list would include: (i) consideration of all the technologies and sectors implemented in ESTD (P2M, P2G, etc), (ii) limiting the yearly resource consumption and unit production in Dispa-SET, (iii) further investigations regarding the choice of adequacy indicators, including more than only electricity, and finally (iv) study of a multi-cell case study (e.g. European countries).

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Appendices

A Models description

This appendix makes the inventory of the input/output of the models in question in this work: EnergyScope TD and Dispa-SET.

A.1 EnergyScope TDF inputs

In Table 19 are gathered the main the ESTD inputs.

Input	**Content**	**format**
Time Series	-Renewable availability factors -EUD distribution	hourly time series
c_p_t	Technology and renewable source capacity factors	hourly time series
RESOURCES	-Availabiliy [GWh] -Operational cost [M€/GWh] -Construction and operational CO_2 emissions $[ktCO_2 - eq/\text{GWh}]$	lines : resources columns : features
User defined	- Typical days inputs - Economical / political inputs - Technologies shares - Electric vehicles features - Networks features	/
EUD	Yearly demand for each EUT	/
layers_in_out	Technologies input/output layer flows	lines : technologies columns : layers
TECH	Technology specifications : - Investment cost: c_inv [M€/GW] - Maintenance cost: c_maint [M€/GW/yr] - Construction GWP: gwp_constr [ktCO_2-eq/GW] -lifetime [yr] - Capacity factor: c_p [-] - Minimum capacity to install: fmin_perc [-] - Maximum capacity to install: fmax_perc [-] -Minimum capacity to install: f_min [GW] -Maximum capacity to install: f_max [GW]	lines : technologies columns : features
STO	Storage technologies input/output layer flows Storage technologies specifications : -charge time [h] -discharge time [h] -storage availibility -storage losses [1/h]	/

Table 19: EnergyScope TD inputs

A.2 EnergyScope Outputs

In Table 20 are gathered the main the ESTD outputs.

Output	**Content**	**format**
Assets.txt	For each technologies - Investment cost: c_inv [M€] - maintenance costs: c_maint [M€/yr] - lifetime [yr] - Minimum installed capacity fmin_perc [-] - Installed capacity: f [GW] - Minimum installed capacity: fmax_perc [-] - Minimum installed capacity: f_min [GW] - Maximum installed capacity: f_max [GW] - Capacity factor: c_p [-] - Investment cost annualization factor: τ [-] - Construction GWP: gwp_constr[$ktCO_2-eq$/GW or GWh]	lines : technologies columns : features
cost_breakdown.txt	technologies computed costs : - Yearly investment cost: c_inv [M€/yr] - Yearly maintenance cost: c_maint [M€/yr] - Yearly operational cost: c_op [M€/yr]	lines : technologies columns : cost types
Distri_E_stored.txt	Electrical storage technology: -storage level -input power -output power	hourly time series For every hour of the year
Distri_TS.txt	Heat storage technology: -storage level -input power -output power	hourly time series For every hour of the year
ElecLayers.txt	Electrical power per technology	hourly time series for each typical day
FREIGHTLayers.txt	Freight mobility power per technology	hourly time series for each typical day
gwp_breakdown.txt	Yearly CO_2 emissions per technology and resource: -GWP_constr [$ktCO_2-eq/yr$] -GWP_op [$ktCO_2-eq/yr$]	lines : technologies columns : emission types
H2Layers	H_2 power per technology	hourly time series for each typical day
HTLayers.txt	HT heat power per technology	hourly time series for each typical day
LTLayers.txt	LT heat power per technology	hourly time series for each typical day
losses.txt	total EUT losses	lines : EUT columns : losses
PASSENGERSLayers.txt	Passenger mobility power per technology	hourly time series for each typical day
YearBalance.txt	Yearly consumption/production per technology	lines : technologies columns : layers

Table 20: EnergyScope TD Outputs

A.3 Dispa-SET Inputs

In Table 21 are gathered the main the Dispa-SET inputs.

Input	**Content**	**format**
TotalLoadValue.csv	- Electricity EUD [MW]	hourly time series One file per zone
Flexible demand	- percentage of the load that can be rescheduled [-]	scalar (or time series) One file for all zones
OutageFactors.csv	For each production unit : - percentage of the installed capacity out of service [-]	hourly time series One file per zone
PowerPlants.csv	For each technology : Fuel,Efficiency MinUpTime, MinDownTime, RampUpRate RampDownRate,StartUpCost__pu,NoLoadCost__pu RampingCost,PartLoadMin,MinEfficiency StartUpTime,CO2Intensity,CHPType CHPPowerToHeat, CHPPowerLossFactor, COP Tnominal, coef_COP_a, coef_COP_ STOCapacity, STOSelfDischarge, STOMaxChargingPower STOChargingEfficiency, CHPMaxHeat	lines : typical units columns : features One file for all zones
AvailabilityFactors.csv	Availability factors [-] for : - PV, WTOF, WTON, HROR, Hydro dams	hourly time series One file per zone
load shedding	- percentage of the load that can be shedded [-]	scalar (or time series) One file for all zones
NetTransferCapacities.csv	For each interconnection line [MW]: Net transfer capacity	hourly time series: One file for all zones
CrossBorderFlows.csv	Historical interconnection flows [MW]	hourly time series One file for all zones
ScaledInflows.csv	For each hydro plant - Normalized inflows [-]	hourly time series One file per zone
ScaledLevels.csv	For each hydro plant - Normalized storage levels [-]	hourly time series One file per zone
HeatDemand.csv	For each heat zone - heat demand [MW]	hourly time series One file for all zones
Temperatures.csv	Zone temperature [$°C$]	hourly time series One file for all zones
Demand flexibility	Number of equivalent storage hours for the flexible demand [h]	scalar In the configuration file
Share of quick start	Share of the 2U reserve that can be covered by quick start units [-]	scalar In the configuration file
Prices	- Price of CO_2 - Price of *HeatSlack* [€/MWh] - Price of load shedding [€/MWh] - Price of resources [€/MWh] - Value of lost load [€/MWh] - Price of spillage [€/MWh] - Water value [€/MWh]	scalar (or time series) In the configuration file

Table 21: Dispa-SET inputs

A.4 Model nomenclature correspondence

In Table 22 are described all the technology correspondences between EnergyScope TD and Dispa-SET.

Technology ESTD	**Fuel ESTD**	**Technology Dispa-SET**	**Fuel Dispa-SET**
CCGT	NG	COMC	GAS
COAL_US	COAL	COMC	HRD
COAL_IGCC	COAL	STUR	HRD
PV	RES_SOLAR	PHOT	SUN
GEOTHERMAL	RES_GEO	STUR	GEO
NUCLEAR	URANIUM	STUR	NUC
HYDRO_RIVER	RES_HYDRO	HROR	WAT
NEW_HYDRO_RIVER	RES_HYDRO	HROR	WAT
WIND_ONSHORE	RES_WIND	WTON	WIN
WIND_OFFSHORE	RES_WIND	WTOF	WIN
IND_COGEN_GAS	NG	STUR	GAS
IND_COGEN_WOOD	WOOD	STUR	BIO
IND_COGEN_WASTE	WASTE	STUR	WST
IND_BOILER_GAS	NG	HeatSlack	/
IND_BOILER_WOOD	WOOD	HeatSlack	/
IND_BOILER_OIL	LFO	HeatSlack	/
IND_BOILER_COAL	COAL	HeatSlack	/
IND_BOILER_WASTE	WASTE	HeatSlack	/
IND_DIRECT_ELEC	ELECTRICITY	P2HT	OTH
DHN_HP_ELEC	ELECTRICITY	P2HT	OTH
DHN_COGEN_GAS	NG	STUR	GAS
DHN_COGEN_WOOD	WOOD	STUR	BIO
DHN_COGEN_WASTE	WASTE	STUR	WST
DHN_COGEN_WET_BIOMASS	WET_BIOMASS	STUR	BIO
DHN_BOILER_GAS	NG	HeatSlack	/
DHN_BOILER_WOOD	WOOD	HeatSlack	/
DHN_BOILER_OIL	LFO	HeatSlack	/
DHN_DEEP_GEO	RES_GEO	HeatSlack	/
DHN_SOLAR	RES_SOLAR	HeatSlack	/
DEC_HP_ELEC	ELECTRICITY	P2HT	OTH
DEC_THHP_GAS	NG	HeatSlack	/
DEC_COGEN_GAS	NG	STUR	GAS
DEC_COGEN_OIL	LFO	STUR	OIL
DEC_ADVCOGEN_GAS	NG	STUR	GAS
DEC_ADVCOGEN_H2	H2	STUR	HYD
DEC_BOILER_GAS	NG	HeatSlack	/
DEC_BOILER_WOOD	WOOD	HeatSlack	/
DEC_BOILER_OIL	LFO	HeatSlack	/
DEC_SOLAR	RES_SOLAR	HeatSlack	/
DEC_DIRECT_ELEC	ELECTRICITY	P2HT	OTH
PHS	ELECTRICITY	HPHS	OTH
DAM_STORAGE	ELECTRICITY	HDAM	OTH
BATT_LI	ELECTRICITY	BATS	OTH
BEV_BATT	ELECTRICITY	BEVS	OTH
PHEV_BATT	ELECTRICITY	BEVS	OTH
TS_DEC_DIRECT_ELEC	Heat	THMS	/
TS_DEC_HP_ELEC	Heat	THMS	/
TS_DEC_THHP_GAS	Heat	THMS	/
TS_DEC_COGEN_GAS	Heat	THMS	/
TS_DEC_COGEN_OIL	Heat	THMS	/
TS_DEC_ADVCOGEN_GAS	Heat	THMS	/
TS_DEC_ADVCOGEN_H2	Heat	THMS	/
TS_DEC_BOILER_GAS	Heat	THMS	/
TS_DEC_BOILER_WOOD	Heat	THMS	/
TS_DEC_BOILER_OIL	Heat	THMS	/
TS_DHN_DAILY	Heat	THMS	/
TS_DHN_SEASONAL	Heat	THMS	/
SEASONAL_NG	NG	/	GAS
SEASONAL_H2	H2	/	HYD

Table 22: Correspondence table for the technologies nomenclature in EnergyScope TD and DISPA-SET

In Table 23 are described all the fuel correspondences between EnergyScope TD and Dispa-SET.

Fuel EnergyScope TD	**Fuel Dispa-SET**
NG	GAS
COAL	HRD
RES_SOLAR	SUN
RES_GEO	GEO
URANIUM	NUC
RES_HYDRO	WAT
RES_WIND	WIN
WOOD	BIO
WASTE	WST
ELECTRICITY	OTH
H2	HYD

Table 23: Correspondence between fuel terminology in EnergyScope TD and DISPA-SET

B Models adaptations

Some details about the model adaptations are provided in this appendix. It concerns the implementation of different *HeatSlack* prices in Dispa-SET.

B.1 New *HeatSlack* management in Dispa-SET

This section will describe the modifications made to the UCM_h.gms file which are necessary to deine a different $HeatSlack\_price\_layer$ for reach heat layer. A new parameter is set : $HeatSlack\_price\_layer(n\_th)$. This parameter value is set as described in the B. In the file, this is written as :

$$
\begin{aligned}
&HeatSlack\_price\_layer(n\_th) \quad \$sameas(n\_th, "BE\_DEC") \quad = p1;\\
&HeatSlack\_price\_layer(n\_th) \quad \$sameas(n\_th, "BE\_DHN") \quad = p2;\\
&HeatSlack\_price\_layer(n\_th) \quad \$sameas(n\_th, "BE\_IND") \quad = p3;
\end{aligned}
$$

Then this parameter needs to be taken into account in the objective function :

$$
\begin{gathered}
EQ\_SystemCost(i)..\\
SystemCost(i)\\
= E =\\
sum(u, CostFixed(u) * TimeStep * Committed(u,i))\\
+sum(u, CostStartUpH(u,i) + CostShutDownH(u,i))\\
+sum(u, CostRampUpH(u,i) + CostRampDownH(u,i))\\
+sum(u, CostVariable(u,i) * Power(u,i) * TimeStep)\\
+sum(l, PriceTransmission(l,i) * Flow(l,i) * TimeStep)\\
+sum(n, CostLoadShedding(n,i) * ShedLoad(n,i) * TimeStep)\\
+sum(n\_th, CostHeatSlack(n\_th,i) * HeatSlack(n\_th,i) * TimeStep * HeatSlack\_price\_layer(n\_th))\\
+sum(p2h2, CostH2Slack(p2h2,i) * StorageSlack(p2h2,i) * TimeStep)\\
+sum(chp, CostVariable(chp,i) * CHPPowerLossFactor(chp) * Heat(chp,i) * TimeStep)\\
+Config("ValueOfLostLoad","val") * (sum(n, (LL\_MaxPower(n,i) + LL\_MinPower(n,i)) * TimeStep))\\
+0.8 * Config("ValueOfLostLoad","val") * (sum(n, (LL\_2U(n,i) + LL\_2D(n,i) + LL\_3U(n,i)) * TimeStep))\\
+0.7 * Config("ValueOfLostLoad","val") * sum(u, (LL\_RampUp(u,i) + LL\_RampDown(u,i)) * TimeStep)\\
+Config("CostOfSpillage","val") * sum(wat, spillage(wat,i));
\end{gathered}
$$

It is also important to note that in the Dispa-SET Configfile, the CostHeatSlack is loaded as equal to one.

B.2 Feedback loop in EnergyScope TD

Constraints need to be added to ESTD in this soft-link. The modifications presented here after are included in the version of EnergyScope TD on this Github: [5].

The following parameters need to be declared in *ESTD_model.mod*. The value is assigned in the *ESTD_main.run*.

Parameter	Description	Default value
fbl_load_shedding_gwh	Biggest load shedding [GWh]	0
fbl_load_shedding_duration	Consecutive hours of biggest load shedding	0
fbl_initial_DispatchPower	Dispatchable power of initial system (including import capacity) [GW]	0
fbl_initial_Const_power	Constant power capacity of initial system [GW]	0
fbl_LackOfPower	K_{elec} (see section 2.3.2)	1

Table 24: Parameters included in ESTD model to implement a feedback loop

New constraints are added in the *ESTD_model.mod*. [Eq.40] ensures a mimimum power capacity ; [Eq.41] imposes a minimum storage level for all technologies able to store electricity ; [Eq.42] ensures that a certain capacity reserve is available. The latter can be ensured by fixing a minimum storage level or adding a certain power capacity of flexible technologies.

$$\begin{array}{l} \#[Eq.40] \\ subject\ to\ mininum\_power\_capacity : \\ sum\{i\ in\ FLEXIBLE\_TECH,\ j\ in\ CONSTANT\_TECH\_ELEC\}(F[i] + F[j] + import\_capacity) \\ >= (fbl\_initial\_DispatechPower + fbl\_initial\_Const\_Power)/fbl\_LackOfPower; \end{array}$$

$$\begin{array}{l} var\ Sto\_level\_min >= 0; \\ \#[Eq.41] \\ subject\ to\ fix\_security\_reserve \\ \{tech\ in\ STORAGE\_OF\_END\_USES\_TYPES[''ELECTRICITY''], h\ in\ HOURS, td\ in\ TYPICAL\_DAYS\} : \\ Sto\_level\_min <= F\_t[tech, h, td]; \end{array}$$

$$\begin{array}{l} \#[Eq.42] \\ subject\ to\ supply\_capa\_margin : \\ (sum\{tech\ in\ FLEXIBLE\_TECH\}F[tech] + import\_capacity - fbl\_initial\_DispatchPower) \\ *fbl\_load\_shedding\_duration \\ >= fbl\_load\_shedding\_gwh; \end{array}$$

Finally, new **SETs** are created. They are declared in *ESTD_data.dat* and called in *ESTD_model.mod*. *FLEXIBLE_TECH* gathers all electricity production technologies dispatchable, in other words for which the power can be easily controlled ; *STORAGE_ELEC_TECH* represents the storage technologies allowing electricity storage ; *CONSTANT_ELEC_TECH* takes into account only electricity production technologies for which the power level is impossible or not convenient to make vary (e.g. nuclear)

$$\begin{array}{l} set\ FLEXIBLE\_TECH := CCGT\ GTUR\ IND\_COGEN\_GAS\ COAL\_US\ ... \\ set\ STORAGE\_TECH\_ELEC := BATT\_LI\ PHS\ BEV\_BATT\ ... \\ set\ CONSTANT\_TECH\_ELEC := NUCLEAR \end{array}$$

C Soft-link

This appendix section presents some details regarding the soft-link methodology. It includes details about data processing, the limitations due to the *HeatSlack* and some words about the choice of definition for indicators.

C.1 Data processing

In this section, the soft-link data processing is described.

C.1.1 Electricity demand

Some data processing is done to build the Dispa-SET electricity EUD time series. The several processing steps are (i) addition of the supplementary loads (e-mobility and P2G) and (ii) addition of the grid losses (that are present in ESTD but not in Dispa-SET).

By defining the electricity EUD time series for ESTD and Dispa-SET $EUD_{ESTD}(h)$ and $EUD_{DS}(h)$ respectively, the computation of the latter is done with the following equation:

$$EUD_{DS}(h) = EUD_{ESTD}(h) * factor + Load_{suppl}(h) * (1 + Loss_{grid}) \tag{6}$$

with $Load_{suppl}(h)$ the extra electrical load time series, taking into account the consumption of the electro-mobility and P2G technologies in the ESTD system. This time series is built thanks to the TD distribution provided as output of the ESTD simulation. $Loss_{grid}$ is the parameter representing grid losses in ESTD (typically 4.7% in this work). Those losses are applied to every electricity production. Finally, the last parameter 'factor' is a representation of the grid losses linked to the production of electricity, but not only for the EUD. In other words, electricity produced to power heat pumps is also subject to losses. Therefore, computing these losses as 4.7% of the electrical EUD is not exhaustive. The definition of this factor becomes:

$$factor = \frac{END\_USES\_DEMAND - \sum_h Load_{Suppl}(h) * Loss_{grid}}{\sum_h EUD_{ESTD}(h)} \tag{7}$$

with END_USES_DEMAND directly taken from the ESTD output 'YearBalance.txt' and representing the yearly electrical EUD plus the yearly grid losses. Note that the second term of the numerator has to be subtracted, because it is present in equation (6).

Finally, that method is not perfect because grid losses linked to heat generation units are split over the whole year, and not added specifically at the time the electricity is actually consumed by those units. Nevertheless, the method allows the two models to have a similar total yearly electricity demand.

C.1.2 Heat demand

Unlike in ESTD where one single Low Temperature (LT) heat demand time series is given as input, in Dispa-SET two time series are required (for DEC and DHN). The ESTD simulation results in a share of the LT heat production between DEC and DHN. Based on this distribution, the Dispa-SET heat demands are built.

To create the DEC and DHN demand time series, two elements must be considered: (i) the ESTD LT heat production distribution and (ii) the additional heat losses linked to the units production DHN heat.

First, regarding the ESTD production share, one first parameter is computed based on the ESTD outputs. It represent the percentage of LT heat produced with DEC technologies:

$$f_{DEC\_EUD\_Perc} = \frac{DEC_{EUD\_year}}{DHN_{EUD\_year} + DEC_{EUD\_year}} \tag{8}$$

where the yearly DEC and DHN heat EUD (DEC_{EUD_year} and DHN_{EUD_year} respectively) are available in the 'YearBalance.txt' ESTD output.

Then, the DEC and DHN demand time series ($DEC_{EUD}(h)$ and $DHN_{EUD}(h)$) are built based on the ESTD LT heat demand $LT_{EUD}(h)$:

$$DHN_{EUD}(h) = LT_{EUD}(h) * (1 - f_{DEC\_EUD\_Perc}) * factor \tag{9}$$

$$DEC_{EUD}(h) = LT_{EUD}(h) * f_{DEC\_EUD\_Perc} \tag{10}$$

In the DHN equation, one additional term is added: 'factor'. The latter represents the DHN production losses. Indeed, it is computed as:

$$factor = \frac{Prod_{DHN} - Loss_{Sto\_DHN} - DHN_{EUD\_year}}{Prod_{DHN} - Loss_{Sto\_DHN}} \tag{11}$$

with $Prod_{DHN}$ the yearly DHN heat production and $Loss_{Sto\_DHN}$ the yearly heat losses linked to the DHN storage units. Thanks to this definition, the factor only represents DHN production losses.

To sum up, this way of computing the DEC and DHN heat demands has for benefit to perfectly match the total EUD in both ESTD and Dispa-SET. However, the drawback is that it imposes that the heat EUD is met by the DEC and DHN all year long. In an imaginary scenario, it could be that ESTD decides to use DHN units only during summer month.

C.2 Capacity margin

Several options were tested in order to find the right definition of the capacity margin $Capa_{marg}(h)$. Two elements make this task uneasy: (i) no formal definition is present in the literature and (ii) in the case of future energy systems, where a high RES share and electrification of heat sector are expected, only taking into account the electrical production units is not sufficient. Anyway, two different definitions were tested:

- Only electrical margin

  In this first case, the capacity margin is defined only by the flexible production units (CCGT, gas units, etc), the electricity storage units and the electricity peak demand. Two components are at the numerator: (1) the difference between the installed capacity of flexible unit i and its actual production at hour h and (2) the available power from storage unit j at hour h. Peak_Load represents the highest electricity demand throughout the year.

$$Capa_{marg}(h) = \frac{\sum_i (Capa(i) - Prod(i,h)) + \sum_j Sto_{elec}(j,h)}{Peak\_Load} \tag{12}$$

By using this definition, one problem occurs: if the system has an important part of the heat sectors powered by P2H technologies, the capacity margin often falls to zero. Indeed, for instance, those units could be heat pumps, used as flexible loads and storing heat every time power is available. This reasoning is also applicable to the power used to store electricity.

- Including heat electrification

  In order to include the flexibility load in the capacity margin definition, one possibility is to add a term $Load_{Flexible}(h)$. This latter represents, at every hour (h), the electrical load used to store heat or electricity. Similarly, the Peak_load term here represents the maximum electrical load, subtracted from the maximum $Load_{Flexible}$.

$$Capa_{marg}(h) = \frac{\sum_i (Capa(i) - Prod(i,h)) + \sum_j Sto_{elec}(j,h) + Load_{Sto}(h)}{Peak\_Load - Load_{Flexible\_}max} \tag{13}$$

C.3 Limitation - Varying HeatSlack prices

As said earlier, one of the model adaptation made in Dispa-SET was the possibility to separate the three heat layers. Then, they each have their own *HeatSlack*, and *HeatSlack* price. Another adaptation was to fix these prices independently from one another. For example, a more expensive price for the DHN heat layer would result in less use of *HeatSlack* in the concerned layer. An example of this is shown in Figure 35.

In this figure, one can see that the change in IND *HeatSlack* price affect not only the IND heat layer, but the DHN heat layer. In the latter, when the IND *HeatSlack* price increases, the DHN COGEN unit produces less which affects the DHN *HeatSlack*.

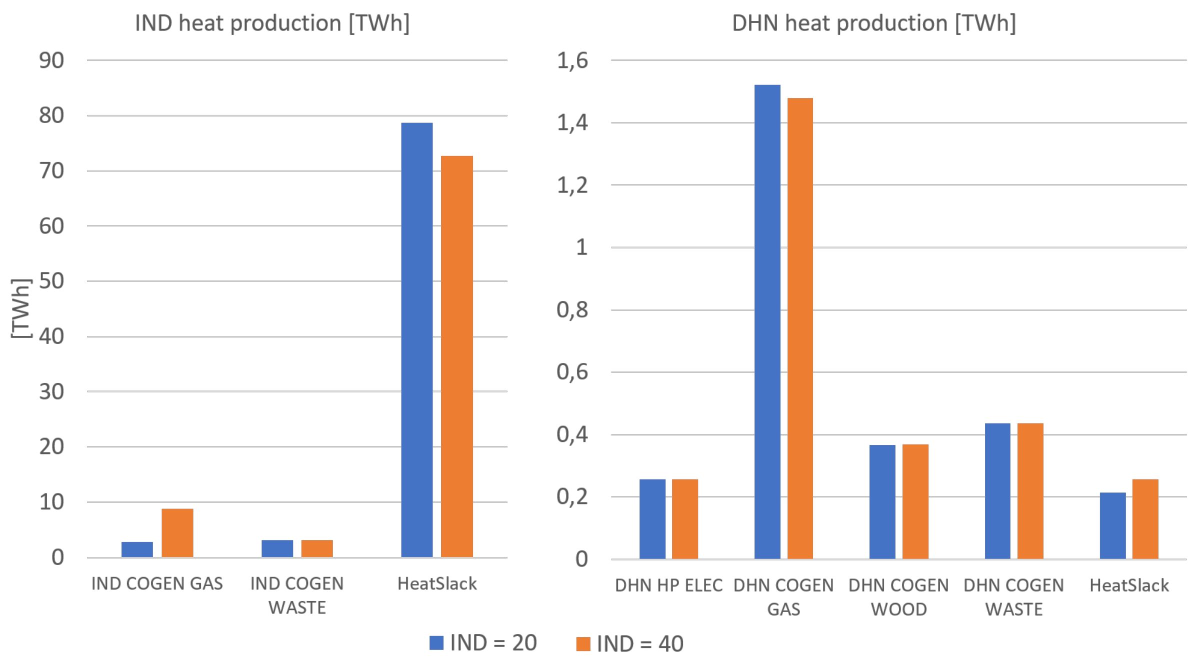

Figure 35: Production in two heat layers (INd and DHN) when the IND *HeatSlack* price is set to 20 and 40 [€/MWh].

The said *HeatSlack* prices were varied so that the yearly production of the later would match within 5%, comparing the two models. The results are displayed in appendix **??**. However, for the BE2015 case, varying prices within one layer can have an effect on the three layers at the same time.

Parameters		**value**
Price of *HeatSlack* [€/MWh]	DEC	16.7
	DHN	25.25
	IND	20.32

Table 25: The different parameters that had to be user defined for the BE2015 Case

This is so because all heat layers contain CHP units. Hence, if one layer uses the *HeatSlack* more, it will use its CHP unit less, producing less electricity. The lack of electricity generation will have to be cover by other units.

To illustrate this, a quick experiment is carried out (see Figure 36). The DHN *HeatSlack* price is increased while the IND and DEC prices are kept constant. This is done twice, with two different IND *HeatSlack* prices of 20 and 40 [€/MWh].

One would expect the use of the DHN *HeatSlack* to decrease as the price in the DHN heat layer increases. This appears clearly in the case where IND *HeatSlack* price = 40 [€/MWh]. However, when IND *HeatSlack* price = 20 [€/MWh], the DHN *HeatSlack* production remains constant. This proves the impact of changing the *HeatSlack* price, within a layer, on the other layers.

Still in the same idea, the price of the *HeatSlack* in the IND layer has an effect on the DEC *HeatSlack* rather than on the IND *HeatSlack* production itself.

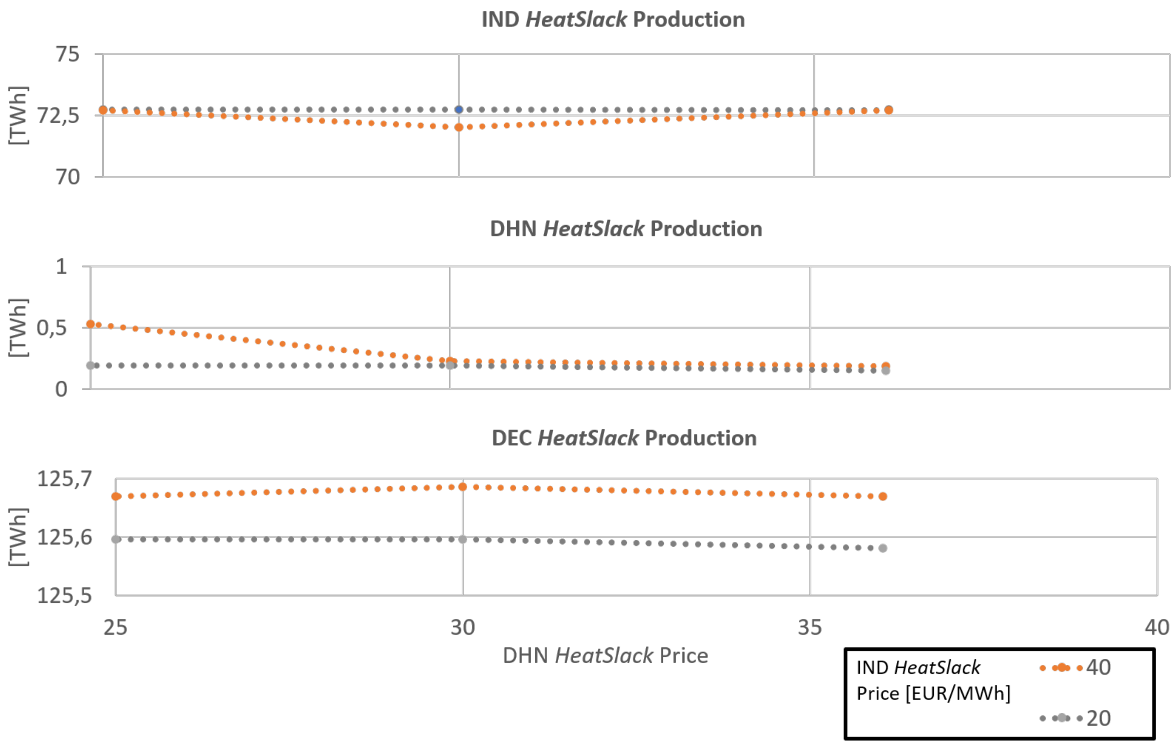

Figure 36: *HeatSlack* production in all heat layers as a function of the DHN and IND *HeatSlack* Price. This illustrates how the production dispatch in one heat layer affects other heat layers and that varying *HeatSlack* prices should be then carefully

The conclusion which can be drawn from these results is that changing the price of the *HeatSlack* in one layer, has an impact on the other layers. Hence, the methodology to fix *HeatSlack* prices needs to be improved. This will be an important point in the discussion, in section 6.

D Study cases: results

This appendix gathers further analysis regarding the studied cases presented in this work.

D.1 Belgium: high RES share

RES production analysis

In figure 37, one can see the monthly RES production for the two models and the maximum possible production. The latter is simply the sum over the month of the product of the installed capacity and the availability factors. This graphs shows that EnergyScope TD can sometimes overestimate the RES production (mainly during autumn and winter month). On the other hand, the production is underestimated during spring and winter month. The overall difference between a model production and the maximum possible production will represents the curtailment. Overall, the curtailment in EnergyScope Td is close to 0, because the TDs are chosen to minimise the errors between the approximate and real duration curve. According to Dispa-SET, curtailment might be a little higher when optimizing its dispatch. this shows EnergyScope might be underestimating overall curtailment.

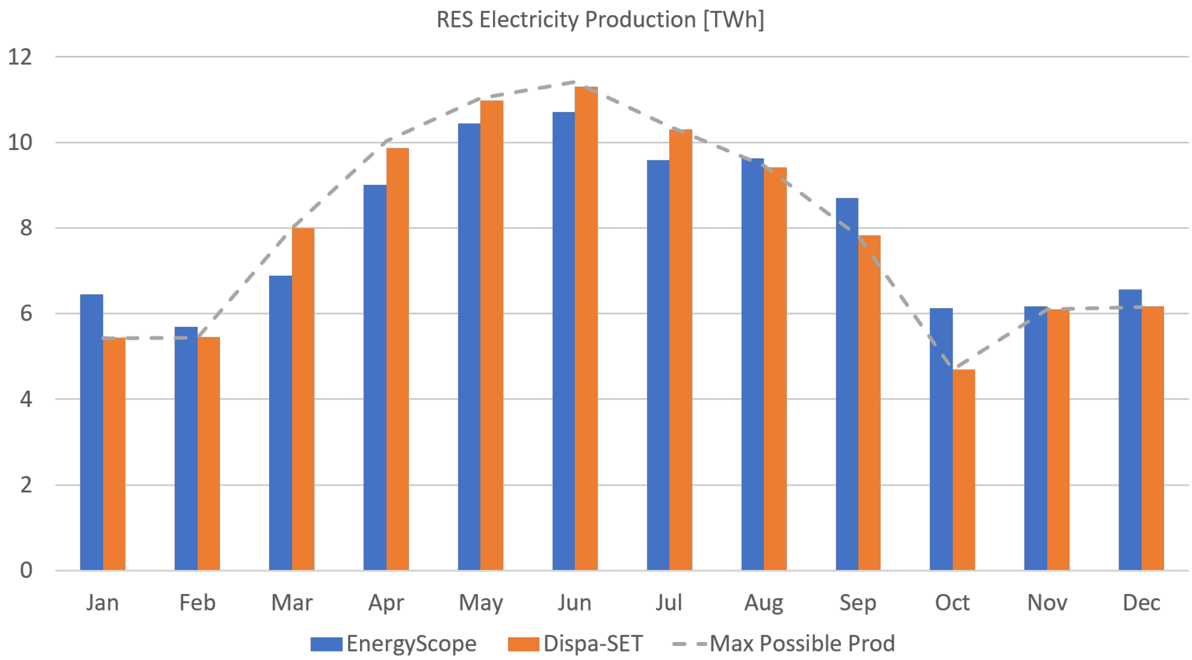

Figure 37: Case 'Belgium: high RES share': RES production differences between ESTD and Dispa-SET optimisation. The maximum production according to the availability factors is presented as well. This shows how EnergyScope can sometimes overestimate the RES production.

DHN storage analysis

The goal of this section is to give explanations about the DHN storage curves of ESTD and Dispa-SET for the case 'Belgium: high RES share'. Those curves are depicted in

Figure 38.

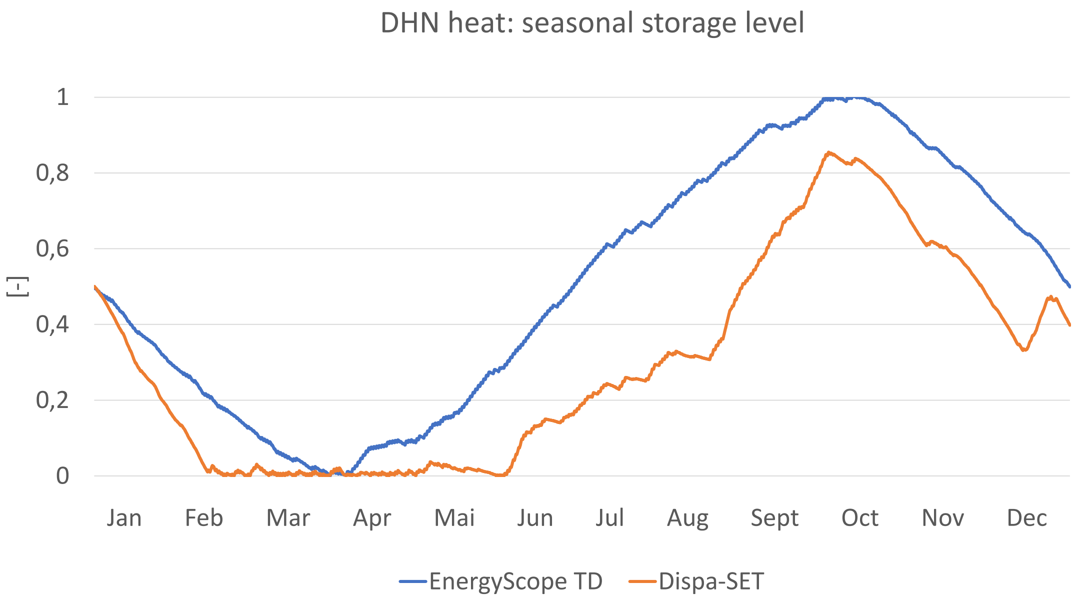

Figure 38: Case 'Belgium: high RES share': DHN storage curves analysis

In this previous figure, on can spot that unlike ESTD, Dispa-SET will avoid keeping heat stored for a long time. This is due to two elements: first the storage losses being proportional to the storage level, Dispa-SET will tend to keep the storage level as low as possible. Second, as illustrated in Figure 39, Dispa-SET consumes more electricity in DEC storage than ESTD does. This results from the dispatch optimisation. As a consequence, this electricity is not available for DHN storage. This explains why from January to Mai, the DHN storage level in Dispa-SET remains lower than the one in ESTD.

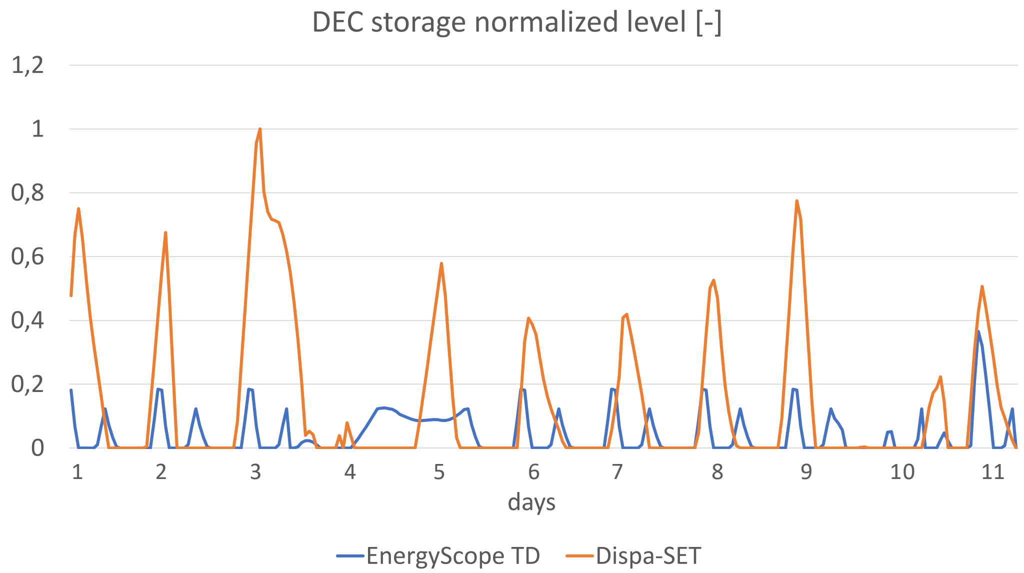

Figure 39: Case 'Belgium: high RES share': DEC storage levels analysis for spring month. Dispa-SET uses more DEC storage than ESTD

After that, another difference between the two curves in Figure 38 is that the Dispa-SET storage level never reaches its maximum. To explain that, let's have a look at Figure 40. In the latter, the heat management strategies of ESTD and Dispa-SET are compared. Those four figures describe the monthly heat production (DEC, DHN and IND) from March to September.

The first interesting element to notice is that the DEC heat production is similar in the two models. Only in April and May, Dispa-SET uses more the DEC storage. The higher production of DEC heat is a direct consequence of the greater use of DEC storage.

After that, obviously by keeping in mind the storage curves, the DHN production is higher in ESTD from April to August. During those month, one can see that Dispa-SET uses more the IND DIRECT ELEC unit. Then, there seems to be a trade-off between electricity consumed for the IND or DHN layer. While ESTD prefers to store DHN heat and using the IND COGEN GAS, Dispa-SET chooses to use the IND electrical resistance and lower the production of the CHP unit. This is a result of the economical dispatch performed by Dispa-SET. Then, it will power the IND electrical resistance with free electricity (from RES), sparing the gas that would have been required for powering the CHP.

To confirm that, in September, it is the other way round. Dispa-SET produces more IND heat and electricity with the CHP, and therefore electricity is available to power the DHN heat pumps. This is the period when the Dispa-SET DHN storage curves is steeper than the one of ESTD.

Finally, even if it is hard to prove, there seems to have a correlation between the use of the IND DIRECT ELEC and the RES electricity available. Indeed, as shown in Figure 37, from April to July, both the RES production and the IND electrical resistance consumption are higher in Dispa-SET. In contrast, in September, we are in the reverse situation. ESTD RES production is overestimated, then the CHP does not need to produce as much electricity as in Dispa-SET, therefore the IND DIRECT ELEC unit (and *HeatSlack*) in ESTD are more used to meet the IND heat demand.

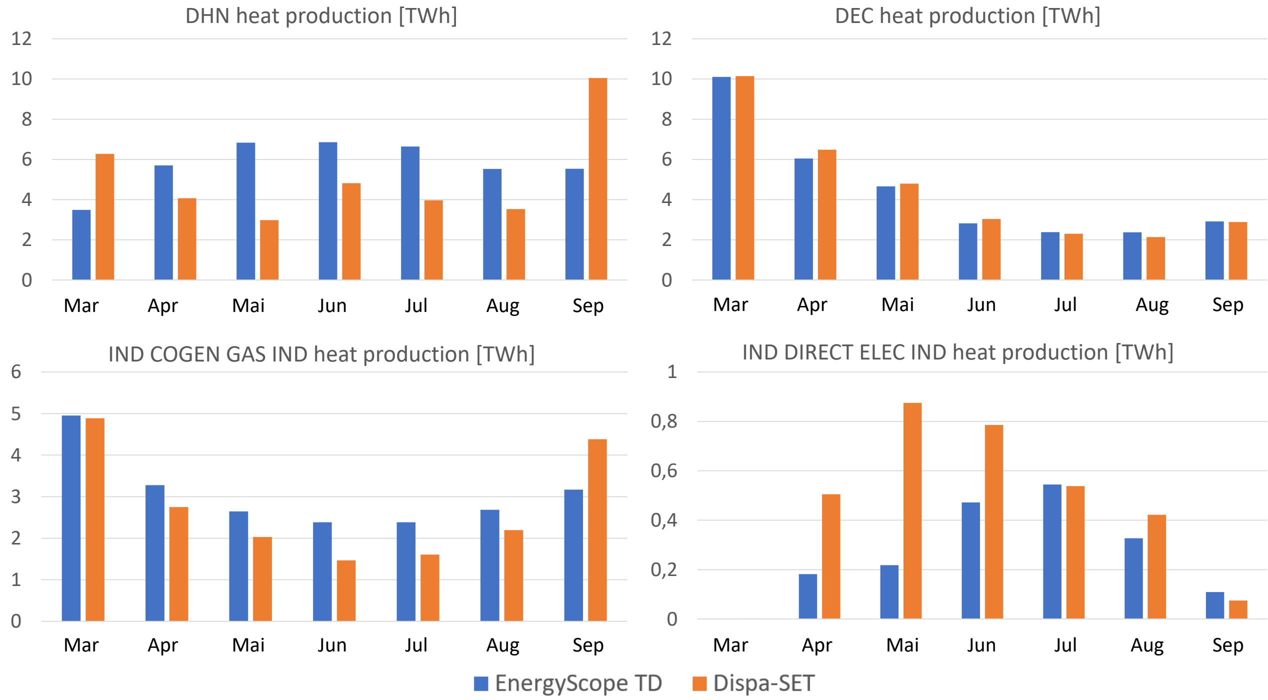

Figure 40: Case 'Belgium: high RES share': heat production differences

D.1.1 Feedback loop

Some parametric studies were carried out in Dispa-SET. First, the CCGT power capacity was modified. Then based on the optimum of this investigation, the influence of storage capacities (electrical or heat) was assessed. Indicators analysed are the ENS, the load shedding, the curtailment and the capacity margin.

CCGT power increase

A parametric study has been carried out to study the impact of increasing the power capacity of a flexible unit (CCGT) on the indicators defined in this work. This was a first attempt to characterise the lack of power capacity of a system. This study has been carried out on the 'High RES Share' scenario. The total amount of ENS to supply is of 47 GWh.

The results of this parametric analysis are depicted in Figure 41. On this graph, the adequacy indicators evolution is described by means of normalized indicators: ratio between a specific indicator value and its initial value. The reference case (**x1**) is the 'Belgium: high RES share' case described in section 3 and the **x1** indicator values are gathered in Table 26.

After analysing this chart, the main advantages of a higher CCGT power prove to be the suppression of the energy not supplied and the decrease of the load shedding. Multiplying the CCGT power capacity by **1.2**, results in no ENS. This corresponds to the factor K_{elec} of 14.2 determined thanks to the parametric study applied on Dispa-SET (see section 4.1). In addition, the total energy shedded drops below 0.4 (45 GWh/year). Regarding the capacity margin and the curtailment, the impact is null.

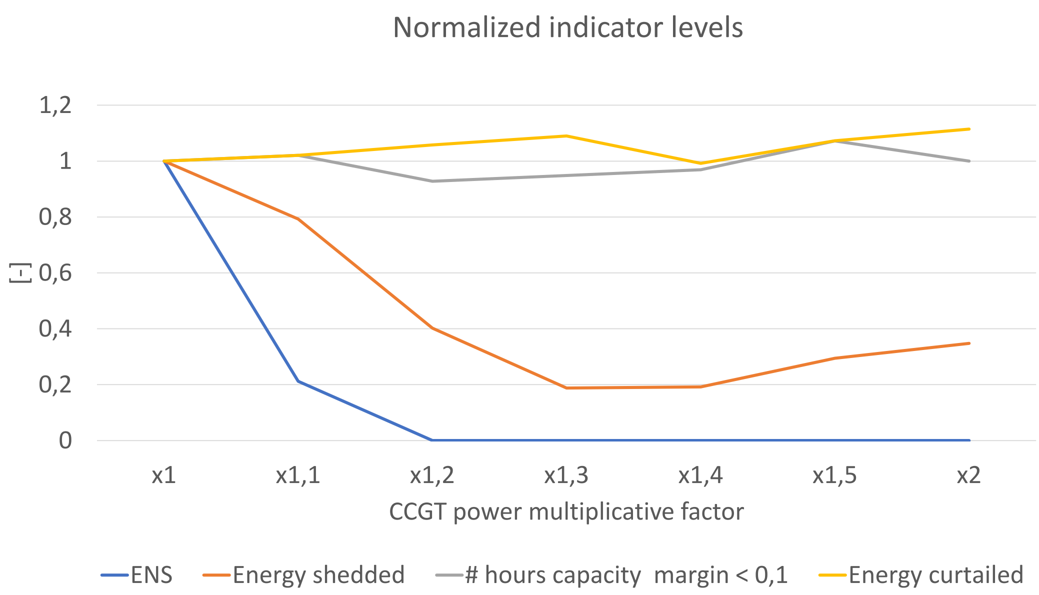

Figure 41: Reference case = 'Belgium: high RES share' (= x1, values in Table 26): the CCGT power increase positively affects the ENS and the load shedding

Indicator	Reference Value
Energy not Supplied [GWh/year]	47
Energy curtailed [GWh/year]	450
Hours with capacity margin < 0.1 [h]	93
Energy shedded [GWh/year]	110

Table 26: Reference indicators values used for the normalization of Figure 41 (= values of case 'Belgium: high RES share')

Still based on the previous figure, the **x1.3** case has been investigated further as well. To give an order of magnitude, the original run had an installed CCGT capacity of 7.65GW. The **x1.3** case results in a capacity of 9.9 GW. On the one hand, this value enables to avoid any ENS. On the other hand, the load shedding reaches around 20% of its initial value. This value is lower than in the **x1.2** case.

Compared to the 'Direct method' presented in section 2.3.2 for the determining the lack of power capacity, this parametric study proves efficient. Indeed, the maximum lost load is around 5 GW in the initial system. So, one could think increase the CCGT of 5 GW would solve lost loads issues. As a matter of fact, only an increase of 2 GW is sufficient. This highlights that due to the complexity of the systems under study, it is uneasy to draw direct conclusions regarding constraints to implement in ESTD.

For the reasons stated above (reduction in ENS and energy shedded), the **x1.3** has been chosen for further simulations.

Concerning the **x1.3** CCGT case, the main indicators are described in Table 27. Regarding behavior indicators, compared to the initial Dispa-SET optimisation of the case 'Belgium: high RES share', the energy curtailed slightly increases. However, the CO_2 emissions due to natural gas consumption are a bit lower. This is explained because a small shift of electricity production occurs between the CCGT and the IND COGEN GAS unit. This former producing a bit more and at a higher efficiency, the total gas consumption globally decreases. For this system with x1.3 CCGT power, all the adequacy indicators become acceptable. Only the reliability indicators (linked to the capacity margin) still need to be improved.

Indicator	**Value**	**Limit**	**Check**
Energy curtailed [GWh]	490	n.a.	+9%
CO_2-eq emissions [$ktCO_2$-eq/year]: natural gas	33 230	n.a.	-0.12%
Load shedding [GWh]	21	5078	v
Max load shedding power [% peak load]	3.25	5.46	v
Average load shedding during 4h [% of peak load]	3.25	8 hours	v
Lost of Load Expectancy [h]	0	3	v
Energy not Supplied [GWh]	0	0.2	v
Minimum Capacity margin [% of peak load]	0.0	0.1	x
Hours with capacity margin < 0.1 [h]	92	0	x

Table 27: Indicators: case 'Belgium: high RES share' + **x1.3** CCGT power capacity'. Percentages in the 'Check' column: evolution compared to the initial Dispa-SET case 'Belgium: high RES share'

So far, by adjusting the CCGT power level, the ENS and load shedding indicators are within the limits. Some further efforts are necessary for having an acceptable system in terms of capacity margin. Also, there is room for improvement regarding the energy curtailment.

The reader should note that these results are similar to the parametric study presented in this work, where electrical demand is reduced. By reducing the demand by 0.875, we reduce the ENS to zero. This indicated a lack of power capacity **x1.14**, which lies between x1.1 and x1.2 detailed here above.

This study proves that (i) increasing the power capacity in equivalent to reducing the power demand, (ii) adequacy requirements are reached through increasing the power capacity.

Storage capacity variations

Here is presented another parametric study on the 'Belgium: high RES share' case with the **x1.3** CCGT power level included: the impact of increasing the storage capacity (both electrical and THMS) on the indictors was studied. For the simulations, a single capacity multiplicative factor is applied either applied to the electrical storage (lithium battery and PHS), or to the heat storage (DHN seasonal and daily DEC). But multiplicative factor is never applied to both at the same time. The results are displayed in 42.

The main relevant result concerns the number of hours with capacity margin lower than 10%. Indeed, on the right of the chart, the positive influence of the electricity storage on the capacity margin is irrefutable. Regarding the heat storage, its impact on the capacity margin is limited. One has to keep in mind that the heat storage level is not included in the capacity margin calculation, which may explain partly this barely flat curve. Anyway, the heat storage has no positive influence on the capacity margin as defined in this work.

Focusing on the load shedding indicator (chart in the middle of Figure 42), there is no clear trend from increasing storage capacity on the total energy shedded with the **x1.3** CCGT power capacity. Although for a value of **x1.4** the electricity storage the load shedding drops.

Keep in mind that the load shedding price (here 1000€/MWh), has an influence on the simulation results. This price was deduced from several official reports but obviously modifying this value would influence the economical dispatch optimisation.

Finally, as far as the curtailment is concerned, the increase of both storage types proves to lower the energy curtailed distinctly. Again in that case, the electricity storage capacity is more important than the heat storage capacity.

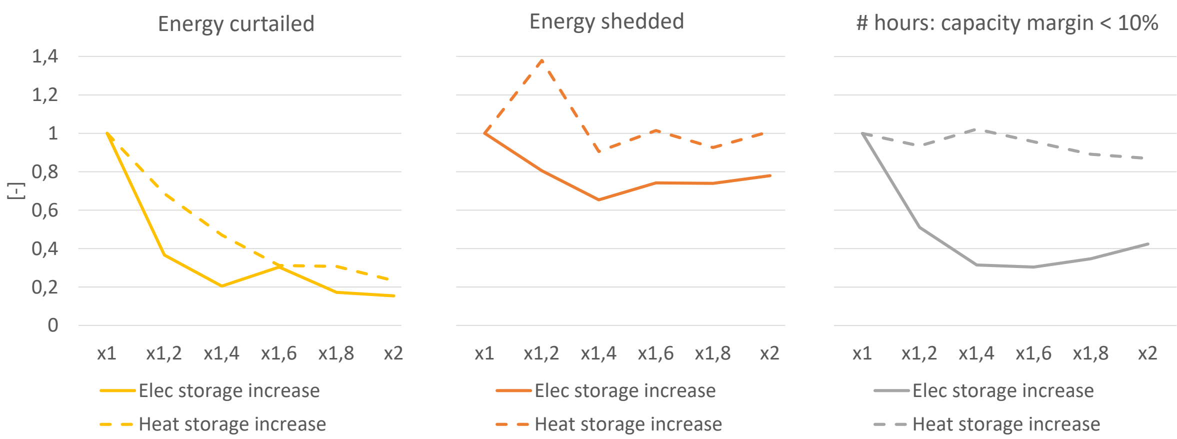

Figure 42: Reference case = 'Belgium: high RES share', **x1.3** CCGT power (= x1, values in Table 28): The electricity storage capacity has a positive impact on the curtailment and the capacity margin. The heat storage capacity has a positive impact on the curtailment, to a lesser extent

Indicator	Reference Value
Energy curtailed [GWh/year]	480
Hours with capacity margin < 0.1 [h]	92
Energy shedded [GWh/year]	21

Table 28: Reference indicators values used for the normalization of Figure 42 (= values of case 'Belgium: high RES share, **x1.3** CCGT power')

D.1.2 Implementation of a Gas Turbine (GTUR) in ESTD

A gas turbine technology was implemented in EnergyScope TD because it has specific features, that where not present yet in the model: high reactivity and low costs. The technical characteristics of this new technology are provided by [18] for the 2030 projections, and are gathered in the following table:

Feature	Value
Efficiency [%]	43
Installation cost [M€/GW]	590
Maintenance cost [M€/GW]	18.6
Lifetime [year]	25
GWP construction [$ktCO_2 - eq$ / GW]	183.79
Capacity factor [-]	0.98

Table 29: Gas turbine: technical features

D.1.3 Adequate system

Comparison between the initial energy system (column ESTD) and the adequate system is proposed in Table 30. In terms of installed capacities, the main difference concerns the new Gas Turbine (GTUR) unit of 2.65 GW. On top of that, one can notice small increase of the CCGT power capacity (+6.5%) as well as the lithium battery storage capacity (+1.3%). On the other hand, the heat units decrease slightly, both for production and storage units.

Units	Initial [GW or GWh]	Adequate [GW or GWh]	Evolution [%]
IND COGEN GAS (elec)	7.08	7.08	none
CCGT	7.65	8.145	+ 6.5
GTUR	0	1.65	new
PV	59.175	59.175	none
WTON	10	10	none
WTOF	3.5	3.5	none
Hydro river	0.12	0.12	none
Lithium battery	53.545	54.25	+ 1.3
PHS	5	5	none
DHN HP ELEC	29.09	28.71	- 1.3
DEC HP ELEC	29.27	29.25	- 0.1
IND DIRECT ELEC	5	5.07	+ 0.1
DHN THMS	22 109	21 663	- 2
DEC THMS	78.76	77.53	- 1.6

Table 30: Installed capacities comparison between initial and adequate energy systems

In Table 31, one can see that the production are similar in the Dispa-SET optimization of the initial and adequate systems. The CCGT produces a bit more, and the PHS unit is more used. Note that the DHN heat pump produces less heat in the adequate case, due to the fact that its storage capacity is lower. Therefore, the storage curves being similar (see figure 43) and the storage losses proportional to the storage level, the total losses are higher in the initial case.

Units	Initial [GWh]	Adequate [GWh]	Evolution [%]
IND COGEN GAS (elec)	45 295	45 292	none
CCGT	15 720	15 763	+ 0.3
GTUR	0	108	new
PV	61 211	61 217	+ none
WTON	21 232	21 256	+ 0.1
WTOF	12 588	12 593	none
Hydro river	505	506	+ 0.2
Lithium battery(out)	10 601	10 540	- 0.6
PHS (out)	425	461	+ 10.8
DHN HP ELEC	53 074	52 779	- 0.6
DEC HP ELEC	84 793	84 786	none
IND DIRECT ELEC	3 265	3268	none

Table 31: Production comparison between initial and adequate energy systems

In Figure 43, it is interesting to notice that in both cases (initial and adequate), the Dispa-SET DHN storage level never reaches 100%. Notice that the adequate storage capacity is 2% lower than in the initial case. It means that in no way the system has the resources to use the whole installed capacity. Therefore, some installation costs could be spared, by reducing the DHN storage capacity.

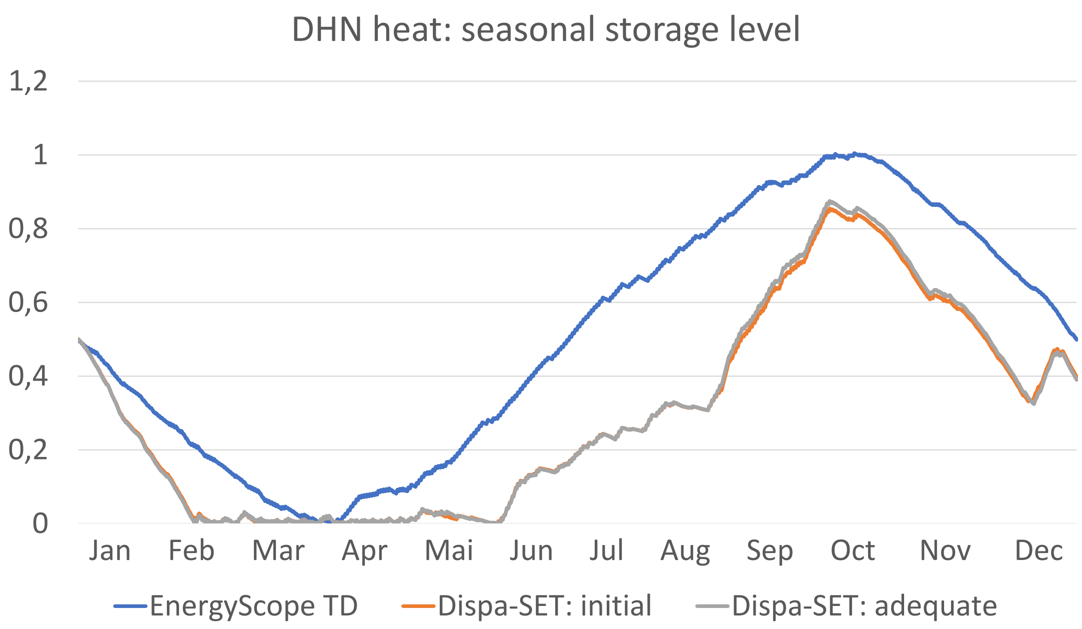

Figure 43: Storage capacity: for 'EnergyScope TD' and 'Dispa-SET: initial': 22 109 GWh ; for 'Dispa-SET: adequate': 21 695 GWh

D.1.4 Adequate system - lowering the DHN THMS

In figure 43, one can observe that the DHN storage level in the 'adequate system' does not fill up to its maximum.

We then thought, that the installed capacity could then be decreased, to save money on the capital investments in such a unit. Recall, 22 TWh of thermal storage are installed in this scenario by EnergyScope Typical Days (ESTD).

The capacity of the thermal storage as then decreased down to 0.86 (19 TWh) of its level and simulations were carried out. The adequacy proved to be exactly the same than in the previous case. The only difference is that the storage filled up to its maximum value (See figure 44).

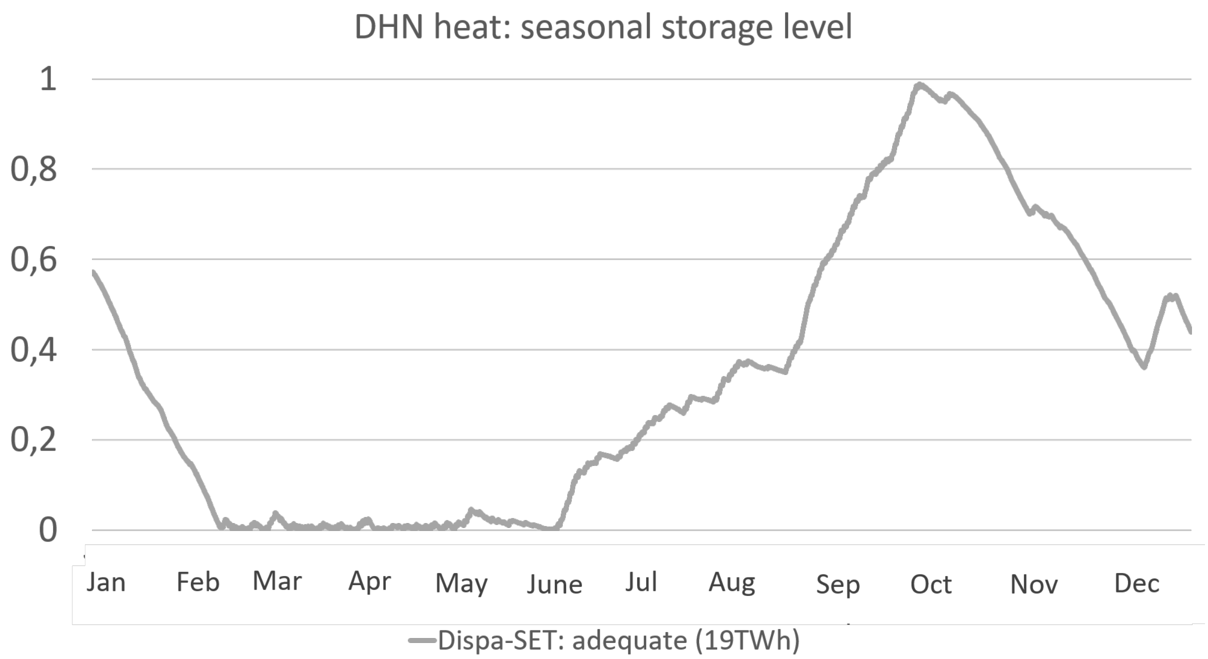

Figure 44: case 'Belgium: high RES share': graph showing the storage level through the year, for the adequate system with storage capacity of 19TWh

D.2 Belgium: energy mix

Some simulation results are presented here, about the case 'Belgium: energy mix'.

D.2.1 Adequate system

In Tables 32 and 33 are described the installed capacities and production per unit respectively, for the study case 'Belgium: energy mix'.

Units	Initial [GW or GWh]	Adequate [GW or GWh]	Evolution [%]
NUCLEAR	5.6	5.6	none
GEOTHERMAL(elec)	4	4	none
CCGT	0	0.82	new
PV	14.9	13.64	- 8.5
WTON	10	10	none
WTOF	10	10	none
Hydro river	0.12	0.12	none
PHS	5.82	5.82	none
DHN HP ELEC	5.45	5.49	+ 0.7
DEC HP ELEC	29.19	29.19	none
IND DIRECT ELEC	1.36	1.22	- 0.10
DHN THMS	3102	3020	- 2.6
DEC THMS	16.92	18.65	+ 10
IND BOILER GAS	3.13	3.17	+ 1.3
IND BOILER COAL	3.47	3.47	none
IND BOILER WASTE	0.97	0.97	none
GEOTHERMAL (DHN)	4	4	none

Table 32: Installed capacities comparison between initial and adequate energy systems

Units	Initial [GW or GWh]	Adequate [GW or GWh]	Evolution [%]
NUCLEAR	38 818	38 769	- 0.1
Imports	10 794	8 268	- 23.4
GEOTHERMAL(elec)	35 040	35 040	none
CCGT	0	2 693	new
PV	15 044	13 787	- 8.4
WTON	20 525	20 452	- 0.4
WTOF	34 919	35 025	+ 0.3
Hydro river	493	492	none
DHN HP ELEC	14 988.3	14 946	- 0.3
DEC HP ELEC	83 756	83 804	+ 0.1
IND DIRECT ELEC	6315	5 610	- 11.1
IND *HeatSlack*	59 006	59 712	+ 1.2
GEOTHERMAL (DHN)	35 024	35 077	+ 0.2

Table 33: Productions comparison between initial and adequate energy systems (Dispa-SET simulations)

E User manual

The aim of this section is to help the reader to understand the soft-link architecture and how to use the soft-link. These tools are available on Github [7].

E.1 Architecture

The following figure describes the architecture of the soft-link tools, in other words all the folders and files necessary for the data coupling between ESTD and Dispa-SET. The main parts are the folders 'Inputs', 'Outputs' and 'SideTools'. The first one mainly gathers the ESTD outputs, the second one the Dispa-SET inputs. Finally, the folder 'SideTools' is the core of the data transfer because it contains the python scripts that build the Dispa-SET inputs.

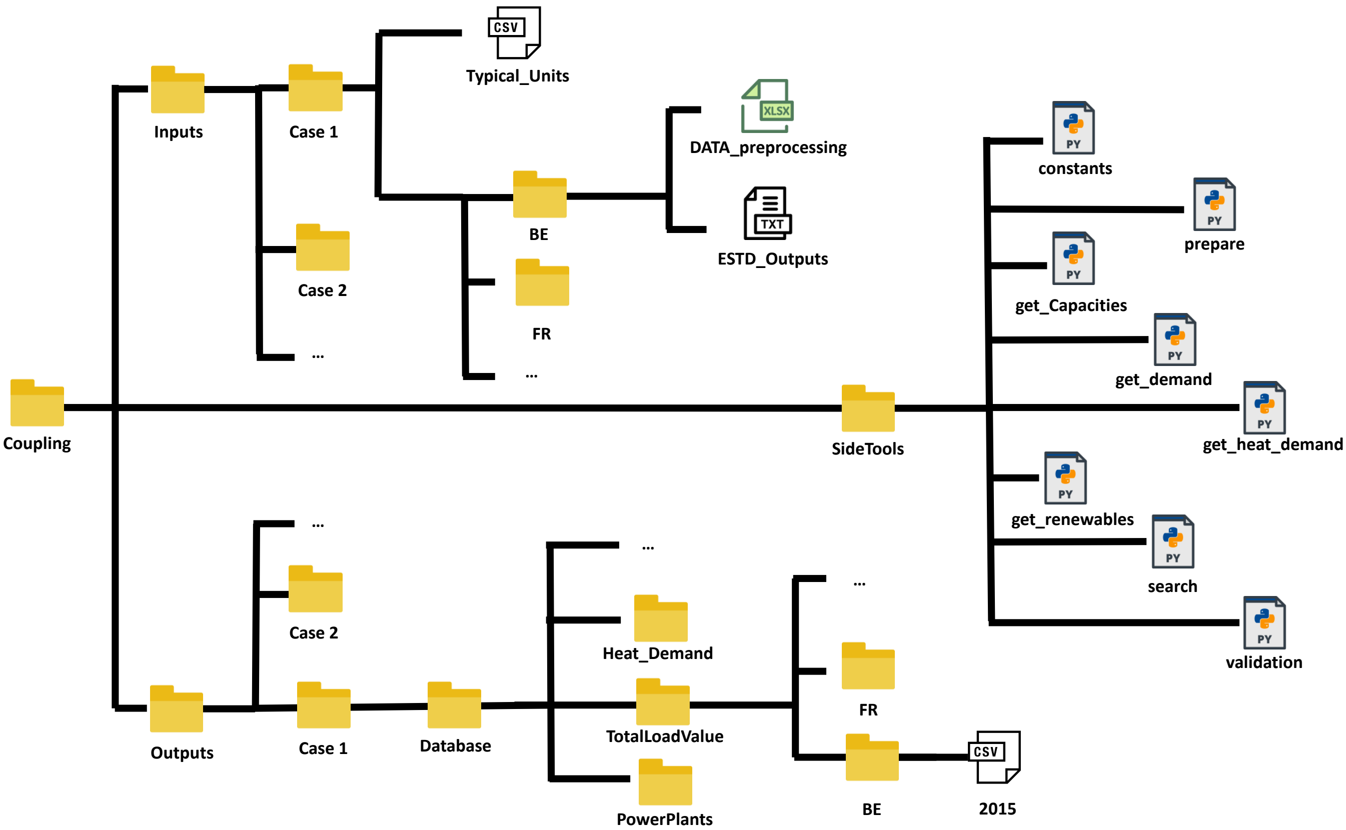

Figure 45: Architecture of the soft-link tools (files and folders)

E.2 Data transfer

In Figure 45, one essential file is called DATA_preprocessing.xlsx. This one contains all the data gathered in the DATA.xlsx ESTD input file. This file is a central piece of the soft-link, because all the scripts are built based on its specific structure, nomenclature and format. Note that there is one such file per country studied.

In more concrete terms, the DATA_preprocessing contains the following sheets:

- **EUD_elec** : this sheet contains the hourly electrical end-use demand ($EUD_{elec}(h)$) for each country. This demand represents the sum of one base load ($Load_B$) and a fluctuating load ($Load_F(h)$). This is the way it is built in EnergyScope TD :

$$\begin{cases} Load_B &= ELEC_{y,households} + ELEC_{y,services} + ELEC_{y,industry} \\ Load_F &= (LIGHT_{y,households} + LIGHT_{y,services} + LIGHT_{y,industry}) * Times\_Series_{\%\_elec}(h) \end{cases}$$

$$EUD_{elec}(h) = \frac{Load_B}{8760} + Load_F(h) \tag{14}$$

$ELEC_{y,households}$	'[DATA.xlsx]2.3 EUD'!B3
$ELEC_{y,services}$	'[DATA.xlsx]2.3 EUD'!C3
$ELEC_{y,industry}$	'[DATA.xlsx]2.3 EUD'!D3
$LIGHT_{y,households}$	'[DATA.xlsx]2.3 EUD'!B4
$LIGHT_{y,services}$	'[DATA.xlsx]2.3 EUD'!C4
$LIGHT_{y,industry}$	'[DATA.xlsx]2.3 EUD'!D4
$Times\_Series_{\%\_elec}(h)$	'[DATA.xlsx]1.1 Time Series'!C4

Table 34: EUD_elec parameters

The format of EUD_elec :

	BE
1	$EUD_{elec}(1)$
...	...
8760	$EUD_{elec}(8760)$

Table 35: EUD_elec format

- **EUD_heat** : this sheet contains the hourly low temperature and high temperature heat end-use demands ($EUD_{H\_LT}(h)$, $EUD_{H\_HT}(h)$) for each country. The low temperature demand represents the sum of base load ($Load_{B\_LT}$) and a fluctuating load ($Load_{F\_LT}(h)$)(only space heating). The high temperature demand is only composed of one base load (Load$_{B_HT}$)$Thisisthewayitisbuilt in EnergyScopeTD$:

$$\begin{cases} Load_{B\_LT} &= H_{LT\_HW_{y,households}} + H_{LT\_HW_{y,services}} + H_{LT\_HW_{y,industry}} \\ Load_{F\_LT}(h) &= (H_{LT\_SH_{y,households}} + H_{LT\_SH_{y,services}} + H_{LT\_SH_{y,industry}}) * Times\_Series_{\%\_sh}(h) \\ Load_{B\_HT} &= H_{HT_{y,households}} + H_{HT_{y,services}} + H_{HT_{y,industry}} \end{cases}$$

$$EUD_{H\_LT}(h) = \frac{Load_{B\_LT}}{8760} + Load_{F\_LT}(h) \tag{15}$$

$$EUD_{H\_HT}(h) = \frac{Load_{B\_HT}}{8760} \tag{16}$$

$H_{LT\_HW_{y,households}}$	'[DATA.xlsx]2.3 EUD'!B7
$H_{LT\_HW_{y,services}}$	'[DATA.xlsx]2.3 EUD'!C7
$H_{LT\_HW_{y,industry}}$	'[DATA.xlsx]2.3 EUD'!D7
$H_{LT\_SH_{y,households}}$	'[DATA.xlsx]2.3 EUD'!B6
$H_{LT\_SH_{y,services}}$	'[DATA.xlsx]2.3 EUD'!C6
$H_{LT\_SH_{y,industry}}$	'[DATA.xlsx]2.3 EUD'!D6
$H_{HT_{y,households}}$	'[DATA.xlsx]2.3 EUD'!B5
$H_{HT_{y,services}}$	'[DATA.xlsx]2.3 EUD'!C5
$H_{HT_{y,industry}}$	'[DATA.xlsx]2.3 EUD'!D5
$Times\_Series_{\%\_sh}(h)$	'[DATA.xlsx]1.1 Time Series'!D4

Table 36: EUD_heat parameters

The format of EUD_heat:

	BE_LT	BE_HT
1	$EUD_{H\_LT}(1)$	$EUD_{H\_HT}(1)$
...	...	...
8760	$EUD_{H\_LT}(8760)$	$EUD_{H\_HT}(8760)$

Table 37: EUD_heat format

- **AvailabilityFactors** : this sheet contains the hourly PV, Wind_Onshore, Wind_Offshore and Hydro_River availibility factors for each country. This is the way it is built in EnergyScope TD :

PV	'[DATA.xlsx]1.2 c_p_t'!M4
$WTON$	'[DATA.xlsx]1.2 c_p_t'!N4
$WTOF$	'[DATA.xlsx]1.2 c_p_t'!O4

Table 38: Availibility Factors parameters

The format of Availability Factors :

	BE_PV	BE_WIND_ONSHORE	BE_WIND_OFFSHORE	...
1	$PV(1)$	$WTON(1)$	$WTOF(1)$	...
...	...	...	...	...
8760	$PV(8760)$	$WTON(8760)$	$WTOF(8760)$	...

Table 39: AvailabilityFactors format

In the case of another country, HYDRO_DAM could be added if necessary.

- **RESOURCES** : this sheet contains all information from EnergyScope TD concerning resources and fuels (corst, emissions, availability).

RESOURCES	Availability [GWh]	gwp_op [ktCO2-eq./GWh]	c_op [M€/GWh]	CO2_op [ktCO2-eq./GWh]
ELECTRICITY	1000000	0.4818	0.08433519	0
GASOLINE	1000000	0.3448	0.08236604	0.25
...	...	...	...	...
WOOD	16484	0.0118	0.02662	0.39

Table 40: Resources format

- **layers_in_out** : this contains the DATA/layers_in_out tab from which we can get the efficiency, COP, PowerToHeatRatio. An example is depicted in Table 41 where 3 resources and 2 tech are represented : Electricity, Natural Gas (NG), Solar energy (RES_SOLAR), and industrial Combined Heat and Power (CHP) unit running on gas (IND_COGEN_GAS) and Photovoltaic Panels (PV). The tab represent succinctly which resources are consumed by which technology, and what is produced. Positive value means a production and a negative value means consumptions. By example, the industrial CHP unit produces electricity and High Temperature heat while consuming Natural Gas. The electrical efficiency is of 43% and a power-to-heat ratio of 0.9565. Emissions are also specified in the table.

	ELECTRICITY	NG	RES_SOLAR	...	HEAT_HIGH_T	...	CO2_IND
ELECTRICITY	1	0	0	...	0	...	0
NG	0	1	0	...	0	...	0
RES_SOLAR	0	0	1		0		0
...	...	...	...	...	...	...	...
IND_COGEN_GAS	0.9565	-2.1739	0	...	1	...	0.43478
PV	1	0	-1	...	...	...	0

Table 41: Layers_in_out format

- **TECH** : takes all the OPEX and CAPEX cost as well as the lifetime considered and emissions for all technologies in EnergyScope TD. The format is depicted on Table 42

		c_inv	c_maint	gwp_constr	lifetime	c_p
Electricity	Nuclear	4845.73	102.93	707.88	60	0.85
	CCGT	771.99	19.73	183.79	25	0.85
	...	...	...	...	...	...
HEAT_HIGH_T	IND_COGEN_GAS	1408.0345	92.61	1024.32	25	0.85
	IND_BOILER_OIL	54.86	1.18	12.32	17	0.95
	...	...	...	...	...	...
STORAGE	BATT_LI	302	0.62	61.3	15	1
	BEV_BATT	0	0	0	1	1

Table 42: TECH tab format

- **STO_sto_eff_in & STO_sto_eff_out** : Both tabs have identical structure with the resources as columns and the storage technologies on the rows, as represented on

Tables 43 and 45. This allows efficient representation of the input and output efficiency of storage technologies

	ELECTRICITY	NG	
PHS	0.87	0	...
BATT_LI	0.95	0	...
...	...	...	...
SEASONAL_NG	0	1	...

Table 43: STO_eff_in tab format

	ELECTRICITY	NG	
PHS	0.87	0	...
BATT_LI	0.95	0	...
...	...	...	...
SEASONAL_NG	0	0.995	...

Table 44: STO_eff_out tab format

- **STO_sto_characteristics** : This tab encompasses several storage characteristics needed to describe their behaviour such as the time it would take to fully charge or discharge the installation, as well as the storage losses. Another characteristic typical to Electric vehicles corresponds to the availability of the technology (i.e. the amount of time per year these can be used to store or discharge electricity).

	charge_time	discharge_time	storage_availability	storage_losses
PHS	4.8309	4.2955	1	0
BATT_LI	4	4	1	0.0002
...	...	...	...	
TS_DHN_SEASONAL	150	150	1	0.0000606
SEASONAL_NG	2256	752	1	0

Table 45: STO_sto_characteristics tab format

E.3 How to use

To use the developed soft-link method, several successive steps and instructions have to be followed:

1. Fill the EnergyScope TD inputs with the adequate format (see EnergyScope TD documentation [1])

2. Run the EnergyScope TD model.

3. Fill the DATA_preprocessing.xlsx file with the EnergyScope TD inputs following the format described in previous section. There is one such file per country studied. Insert this file in the 'Inputs' folder of the coupling architecture, in the folder of the studied country (see Figure 45).

4. Copy all the EnergyScope TD output files and paste them in the same 'Inputs' folder.

5. Fill the Typical_Units.csv file depending on the types of units implemented in EnergyScope TD. Insert it in the 'Inputs' folder of the coupling architecture.

6. Run the prepare.py script. From this run, get the $f\_DEC\_EUD\_Perc$ list and write it in the constants.py Python script.

7. Fill the constants.py script with the simulation parameters (year studied, 'inputs' folder path, technology lists, losses constants, etc)

8. Run all the Python scripts contained in the 'SideTools' folder of the coupling architecture. It results in the creation of the Dispa-SET input files in the 'Outputs' folder of the coupling architecture.

9. Copy the content of the 'Outputs' folder of the coupling architecture and paste it in the Database folder of Dispa-SET.

10. Make sure that all the required Dispa-SET inputs are present in the Database folder of Dispa-SET (see Dispa-SET documentation [6]). If necessary, add supplementary input files.

11. Make sure that the path specified in the Dispa-SET ConfigFile for each input file match the just inserted input file path.

12. Run the Dispa-SET model. Make sure the optimization mode is in **no clustering**, with MTS if the energy system contains long term storage.

13. Analyse the Dispa-SET results, operate the adequacy verification. If necessary, operate the parametric study on Dispa-SET, which aims at suppressing lost loads. Introduce new constraint in ESTD. Finally get a new energy system and analyse the coupling outcomes.

14. Iterate on the same loop if adequacy requirements are not met.

F Further work

In this section, some ideas for improving the soft-link and the models used are presented.

F.1 Piecewise cost function for the *HeatSlack*

Unlike in EnergyScope TD, Dispa-SET model does not restrict the availability of a given resource. As a result, the model can use as much *HeatSlack* with no limits. The Dispa-SET objective function concerning OPEX, if the *HeatSlack* is economically competitive, the latter will be dispatched all year long. As said earlier, this should not be possible, due to the limit on resources availability which can be specified in EnergyScope TD.

To tackle this inconsistency, a piecewise cost function could be implemented. The author of this work have not found a way to do so in the GAMS optimisation. The concept is to give a different price to the *HeatSlack* in each layer, based on the overall consumption.

This method is depicted on Figure 46. On this chart, one can see that depending on the amount of heat produced by the *HeatSlack* in one particular heat layer (industrial heat here), the price of the *HeatSlack* increases. This concept mimics a limit on the resource availability via fixing a huge price for the last part (p3 in this case).

For a *HeatSlack* production quantity q, the piecewise price function $p(q)$ becomes :

$$p(q) = \begin{cases} p_1 & \text{\textit{if} } q \leq q_1 \\ p_2 & \text{\textit{if} } q_1 < q \leq q_2 \\ p_3 & \text{\textit{if} } q_2 < q \end{cases} \tag{17}$$

Assuming that there are two technologies ($t_i = t_1$ or t_2) included in the industrial heat *HeatSlack*, the rules to determine the prices ($p_i = p_1$ or p_2) and quantity tresholds ($q_i = q_1$ and q_2) are based on the next equations:

$$p_i = \frac{res_{price_i}}{\eta_{t_i}} \tag{18}$$

$$q_i = res_{avail_i} * \eta_{t_i} \tag{19}$$

with res_{price_i} and res_{avail_i} the resource price (€/MWh) and resource availability(MWh) of technology t_i respectively. η_{t_i} represents the efficiency of technology t_i.

Obviously, the piecewise function construction implies that p_1 is lower than p_2 and therefore the cheapest *HeatSlack* unit is used first. Also, in this case, in order to prevent the *HeatSlack* production from exceeding the quantity q_2, a price p_3 could be fixed at an extremely high value (e.g. 1 000 000 €/MWh).

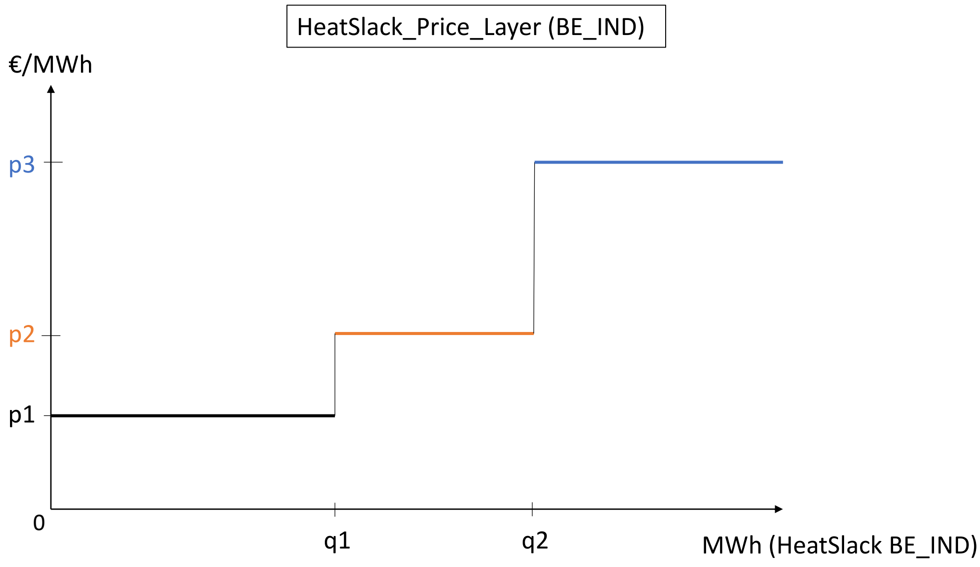

Figure 46: Example of piecewise function of parameter *HeatSlack_Price_Layer* for set **BE_IND**

The authors ran into a problem when trying to implement this in GAMS. In order to keep track of the cumulative quantity of *HeatSlack* produced in a given layer, a variable needs to be introduced. If thiss variabe is defined for the model optimisation, it will work within each optimisation horizon. Hence it will only be able to keep track of a cumulative quantity within each optimisation horizon (typically a few days). *HeatSlack* represents boilers most of the time. These technologies are used to meet heat End Use Demand (EUD) by peaks. In other words, they run at their full capacity over short period of time.

However, the variable which would keep track of cumulative *HeatSlack* production, if implemented in the part of GAMS responsible for the Mid-Term Scheduling (MTS). As a reminder, the MTS solves the problem with fewer equation for the whole year. The main purpose of this is to estimate long term storage level. A cumulative variable in the mid-term scheduling could solve this problem and limit the total quantity of *HeatSlack* for the whole studied period.

F.2 Mid Term Scheduling: new features

An interesting feature to implement in Dispa-SET would be the possibility to limit the (i) the consumption of each resource and (ii) the production of each unit. In this work, it proved to be a limitation. Two problems could be solved thanks to this implementation.

First, a resource availability limit would let the optimisation decide what quantity of *HeatSlack* to use. This is tuned by adjusting the *HeatSlack* price. Second, in ESTD yearly capacity factors are implemented. They impose production limits to the units (modelling outage, maintenance, etc). For the soft-link, there are two possibilities: (i) introduce outage factors time series as input of Dispa-SET. This constraints the optimisation or (ii) let the dispatch model operate the units at full power, all year long. This leads to a more coherent dispatch but productions are overestimated compared to ESTD optimisation.

A possible implementation would be to let the MTS distribute the amount of resource consumed for each single day. A similar distribution would be attributed for the unit productions for each day.

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