Start-Up and Shut-Down Capabilities in Unit Commitment Model with Fully Flexible Temporal Resolution

Effects of Including Start-Up and Shut-Down Ramping Constraints in the Tulipa Energy Model

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Abstract

The transition of the energy grid into a system with higher shares of renewable energy production requires careful investment planning while considering operational characteristics of generators. Generation Expansion Planning (GEP) is used for finding optimal investments, while Unit Commitment (UC) can be used to limit generator operational capabilities, such as via ramping limits, for more accurate modelling. The system may be extended to model custom thermal generator capabilities at the time of their start-up or shut-down, where they may differ from traditional ramping, promoting more precise modelling. However, the inclusion of such detail requires careful managing of model complexity to keep solving time feasible, which can be done with techniques such as Clustered Unit Commitment (CUC), and clustering time blocks while allowing flexible resolution combinations. The latter is known as Fully Flexible Temporal Resolution, and promises managing of model complexity via temporal resolution reductions, while maintaining modelling versatility. The paper targets the unexplored area of including Start-Up and Shut-Down (SU/SD) capability ramping limits alongside a fully flexible temporal resolution in a GEP & CUC model, and contributes by examining the effect of the new capabilities on the run times, investment and operational solutions, and the total system cost of a model with enabled Battery Energy Storage System (BESS) investments. The resulting findings show that the inclusion of the SU/SD capabilities has little effect on the investments and total cost of the model, significantly increases computation time, yet has a noticeable effect on the operational schedule of generators.

1 Introduction

The future-proof expansion of the electrical grid and the transformation of the electrical energy system from a high share of carbon-intensive power generators to systems with larger shares of renewable energy sources is an important challenge in the energy sector. This large-scale undertaking involves substantial investments, and requires long-term planning of the capacity to be installed while aiming to minimize the expanded systems' costs. Computational methods that aid in this task already exist, and are collectively known under the name of Generation Expansion Planning (GEP). These are aimed at finding optimal investments into the energy infrastructure to meet projected demand while fulfilling system constraints. Research into GEP techniques continues to evolve, and some of the proposed models specifically target modelling energy systems with increasing flexibility due to the rising use of Intermittent Renewable Energy Sources (IRES) [1], such as wind and photovoltaic generators. Further research that improves on GEP techniques could promote more accurate expansion planning, possibly facilitating the adoption of IRES.

The flexibility of generators, which describes short-term characteristics such as the speed at which a thermal power plant can change its power output, is not always modelled in GEP. Placing bounds on flexibility requires including fine detail on the generators' status over time, for instance via describing the power output at every hour alongside the limits of its change. This can be achieved with the use of Unit Commitment (UC) as a modelling strategy, where generators are modelled to have variables describing their commitment status (on/off), and have their characteristics limited by constraints such as the ramping limits – describing the maximal difference in power over time. Describing generator flexibility with the use of UC within the GEP model can lead to an explosion in the number of states within the system, increasing computational burden. To manage increased complexity, UC was commonly omitted from GEP modelling, or sometimes ran as a disjoint secondary step on capacities determined by GEP alone [2]. Previous work has also suggested calculating investments at a coarse resolution, and modelling operation at hourly resolution [3], without the use of UC.

However, calculating investments separately, ignoring any operational limits and doing so at a low temporal resolution, has been generally shown to produce inaccurate results [2]. As a particular case, the inclusion of UC within GEP promises to more accurately model realistic expansion planning, especially in systems rich in IRES [1, 4]. Models that employ UC commonly include constraints such as the ramping limits [5], which place a bound on the maximal difference in generators' production between two time steps. However, to more closely describe generator characteristics, ramping limits may need to be modelled for the special case of units starting up or shutting down, as the generators' capabilities may differ at those times. This modelling choice is known as the Start-Up and Shut-Down (SU/SD) capabilities of generators, and it introduces new UC constraints that limit the generator's ramping during the hour at which it is turned on or off, while classical ramping limits apply elsewhere. Start-Up Ramping limits have been previously applied to model binary (slow/fast) start characteristics of generators, associated with lower/higher maintenance costs [6]. In practice, multiple papers in prior literature include SU/SD capabilities [7, 8]. While added ramping constraints may provide a more realistic model of the electrical grid, the addition of these extra constraints generally leads to increased model complexity, causing an increase in solving time [9]. By extension, when introducing the new constraints, model complexity must be managed accordingly.

To combine the benefits of modelling UC within GEP while keeping computation time feasible, previous research has suggested modelling operational constraints only in representative periods within a year [10], avoiding the need to model the entire time horizon. While bulk of the previous work models UC at an hourly resolution [5], another way in which complexity can be managed is by selecting a non-uniform resolution for units, focusing on certain periods in more detail, while modelling others crudely. This approach of partially flexible temporal resolution has been incorporated in [11], which combines investment planning and UC. However, the temporal structure of [11] requires a hierarchy of resolutions, which necessitates the alignment of resolutions of variables in time. Recent research presented in a pre-print article [12] presents a Fully Flexible Temporal Resolution for energy system optimization models, where the resolutions of variables of different assets can be non-uniform in time, and not necessarily a multiple of resolutions of other assets. The possible improvements in temporal reductions can be further combined with simplifications of the complexity of the UC Problem for instance by switching away from the historically commonly used binary formulation, shown to be computationally intensive [13] – where each generating unit has its own binary commitment variable – and instead grouping similar generators together, and describing their commitment with an integer variable. This approach is known as Clustered Unit Commitment (CUC), and has been shown to work well for models that combine GEP with UC [1]. To the best of our current knowledge, the introduction of SU/SD capabilities into a CUC model that is defined using a Fully Flexible Temporal Resolution has not been explored. The combination of the aforementioned modelling strategies with the new constraints constitutes a research gap in the field, and the impact of this combination is to be investigated.

The focus of this paper is exploring the effects of including start-up and shut-down ramping constraints in a CUC model with a fully-flexible temporal resolution. The chosen research methodology is the analysis of quantitative data gathered by running experiments on an energy model that combines these modelling strategies together. This choice is tailored towards an analysis of practical-size systems that can be computed using existing software packages. The base model onto which the constraints were added is the Tulipa Energy Model [14, 15], which supports fully flexible temporal resolution and unit clustering, and has furthermore also been used in [12]. The research examines how the inclusion of SU/SD capabilities and the variation of the temporal resolution affects: 1. the computation time of the model, 2. the values of investment decisions, 3. the cost of the model, and 4. the commitment of generators. As the main contributions of the paper, it is found that the inclusion of SU/SD capabilities into a GEP & CUC model has marginal effect on the investments and total cost of the system, while substantially increasing the computation time, yet having a visible impact on the commitment schedule of generators.

The paper is divided into four further chapters. Chapter 2 explains the mathematical formulation of the Start-Up and Shut-Down capability constraints. Chapter 3 details the test cases that will be ran as part of the experiments, and showcases the numerical results, while Chapter 4 analyses the results and states hypotheses for explanation. Finally, Chapter 5 concludes the findings and suggests future work.

2 Mathematical Formulation

This section begins by providing an overview of how the model works, and later describes in more detail the four operational constraints that limit the start-up and shut-down capabilities of generators in the model. The mathematical formulation of the constraints has been supplied by personal communication [16]. The constraints have been grouped into two further sub-sections, each describing the mathematical formulation of its dedicated set of constraints.

2.1 Overview of the Model

The energy problem is modeled as a set of variables and constraints that are defined at discrete times, following the specification of their temporal resolutions. The variables are set by the solver at the time of solving the problem, while constraints are defined as (in)equalities that compare a formulation, consisting of variables and pre-defined parameters, to zero. A variable does not need to be defined at the same resolution as other variables, for instance the variable describing the flow of energy outgoing from a generator asset may be modeled in two-hour-long intervals, while the same generator's unit commitment status variable can be defined once every three hours. This allowed flexibility to set resolutions to be different for distinct variables is known as Flexible Temporal Resolution.

When planning the optimal expansion of the electrical grid between a starting year and the target year, not all periods in between are modelled, as the problem would become infeasibly large. Instead, a set of years $\mathcal{Y}$ where investments are allowed and the model constraints are applied is selected. This set of years $\mathcal{Y}$ is known as the milestone years. The constraints exist at specifically selected periods that are meant to represent the different times during the year. These are known as the representative periods, denoted by k_y.

The formulations presented in this section can be derived from constraints proposed in prior literature, more specifically the binary unit commitment constraints that do not make use of start variables, presented in [17]. The addition of extra start-up and shut-down capabilities to the model is achieved by extending the existing Tulipa Energy Model [14] code-base to generate additional constraints and include them in the model specifications that are passed to the solver. To find optimal solutions, a solver compatible with Mixed Integer Linear Programming (MILP) problems, such as HiGHS [18] or Gurobi [19], is ran on the model specified by the generated constraints and variables. The Tulipa Energy Model itself is written in the Julia programming language [20], and uses JuMP [21] to interface with the solver directly in the Julia code.

2.2 Start-Up and Shut-Down Ramping Constraints

This section describes the first set of two constraints that limit the generator's start-up and shut-down capabilities. The former of these limits the difference in a generator's outgoing flow (i.e., its power output) between the first timestep at which it is turned on, and the previous time-step, while the latter imposes a limit of the generator's power output between the last step it is producing power at, and the consecutive time step when it is offline.

The formulation of the start-up ramping constraint makes use of variables and parameters as described below. The variable $v^{\text{flow total}}_{a,k_y,b_{k_y}}$ represents the total flow outgoing from an asset a, such as a generator or a battery, in a time block b_{k_y} in a representative period k_y in year $y \in \mathcal{Y}$, and is measured in Megawatts (MW). The variable $v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})}$ represents the number of assets of type a that are operating at time block b_{k_y}, and is unitless. Parameters $p^{\text{ramp up}}_{a,y,k_y,b_{k_y}}$ and $p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}}$ represent the maximal ramping rate measured in MW/h, where the former ramp limit applies at normal operating point of the asset, and the latter applies at time of generator start-up. Parameter $p^{\text{duration}}_{b_{k_y}}$ represents the shortest duration of any flow that makes up $v^{\text{flow total}}_{a,k_y,b_{k_y}}$, and it is included to allow the asset to ramp over the duration of the block and until the next $b_{k_y}+1$. Its omission would lead to under-estimation of the ramp-up capability of the asset for longer time blocks.

The whole formulation for start-up capabilities is presented in equation (1). In short, this formulation constrains the difference of flow between two time steps to be at its maximum the rate of generators that stayed on between the two steps ramping up their power production, plus the rate of new generators being started and ramping up by $p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}}$ in the most recent time step.

$$
\begin{aligned}
v^{\text{flow total}}_{a,k_y,b_{k_y}} - v^{\text{flow total}}_{a,k_y,b_{k_y}-1} \leq{} & (p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} + p^{\text{ramp up}}_{a,y,k_y,b_{k_y}} \cdot (p^{\text{duration}}_{b_{k_y}} - 1)) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \\
& - (p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} - p^{\text{ramp up}}_{a,y,k_y,b_{k_y}}) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y}-1)} \\
& \forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y} \setminus \{b^{\text{start}}\}
\end{aligned} \tag{1}
$$

The formulation for Shut-Down ramping is similar to that of Start-Up ramping. The main difference is the introduction of new, equivalent, parameters for maximum ramp down $p^{\text{ramp down}}_{a,y,k_y,b_{k_y}-1}$ and shut-down ramp $p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}-1}$. The core idea behind the formulation stays the same – the maximal drop in power between time blocks $b_{k_y}-1$ and b_{k_y} cannot exceed that maximal downwards oriented ramp rate of generators that stay on, and the drop of power resulting from generators shutting down. This formulation is shown in (2).

$$
\begin{aligned}
v^{\text{flow total}}_{a,k_y,b_{k_y}-1} - v^{\text{flow total}}_{a,k_y,b_{k_y}} \leq{} & (p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}-1} + p^{\text{ramp down}}_{a,y,k_y,b_{k_y}-1} \cdot (p^{\text{duration}}_{b_{k_y}-1} - 1)) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y}-1)} \\
& - (p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}-1} - p^{\text{ramp down}}_{a,y,k_y,b_{k_y}-1}) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \\
& \forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y} \setminus \{b^{\text{start}}\}
\end{aligned} \tag{2}
$$

To check whether the Start-Up and Shut-Down Ramping constraints actually limit the generator's power output, a visualisation was made where calculated ramping limits are plotted against the generator's actual ramping sequence. This has been depicted in Figure 1. The asset shown there is a Coal power plant, with a Start-Up and Shut-Down ramping limits of 0.38, and a minimal operating point of 0.325, with flows defined at uniform hourly resolution. The dotted lines represent the asset's maximal Ramp-Up and Ramp-Down rates, calculated from formulations (1) and (2), using the values of commitment variables found in the optimal solution. The solid blue line determines the actual ramping of the generator, calculated as the difference of flows between two subsequent time steps.

Two main observations follow from Figure 1. First, the actual difference in flows (the ramping of the generator) never exceeds the limits defined by the calculated constraints. Furthermore, it can be seen that at the start, the generators ramp up at the maximal allowed rate, to meet the spike in demand. This rate is equivalent to the Start-Up Ramping limit, and above the minimal production level. Therefore, the generators make effective use of their Start-Up and Shut-Down capabilities, and seem to never violate the ramping constraints. This visualises that the Start-Up and Shut-Down ramping limits appear to be working as expected.

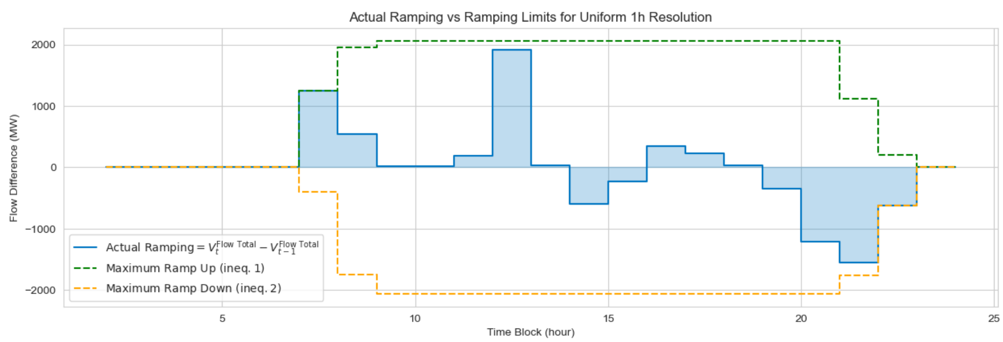


Figure 1: Generator Start-Up and Shut-Down Capabilities compared to ramping in practice, for uniform 1h resolution.

2.3 Tighter Start-Up and Shut-Down Ramping Constraints

This section describes two other added constraints that limit the start-up and shut-down capabilities of generators. These are included alongside the original two constraints, and are aimed at improving the tightness of the formulation. These limit the maximal flow outgoing from an asset a at time blocks b_{k_y} and $b_{k_y} - 1$ respectively.

$$\begin{aligned} v^{\text{flow total}}_{a,k_y,b_{k_y}} \le{} & \min(p^{\max}_{a,y,k_y,b_{k_y}}, (p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} + p^{\text{ramp up}}_{a,y,k_y,b_{k_y}} \cdot (p^{\text{duration}}_{b_{k_y}} - 1))) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \\ & + (p^{\max}_{a,y,k_y,b_{k_y}} - \min(p^{\max}_{a,y,k_y,b_{k_y}}, p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} + p^{\text{ramp up}}_{a,y,k_y,b_{k_y}} \cdot (p^{\text{duration}}_{b_{k_y}} - 1))) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y}-1)} \\ & \forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y} \setminus \{b^{\text{start}}\} \end{aligned} \tag{3}$$

In general, the first tight constraint, presented in (3), limits the outgoing flow of generators of type a at time step b_{k_y} to not exceed the sum of the maximal production of assets that were already committed at time step $b_{k_y}-1$ and the newly started generators' start-up and ramp-up capabilities. The parameters in this formulation are mostly the same as in (1), with the addition of $p^{\max}_{a,y,k_y,b_{k_y}}$, which represents the maximum production level of assets of type a (i.e., the asset's practical capacity) within this time block. When compared to formulation (1), the constraint here limits the maximal power output of assets of type a within the cluster, whereas the previously presented constraint (1) limited the change of power between two subsequent time steps.

$$
\begin{aligned}
v^{\text{flow total}}_{a,k_y,b_{k_y}-1} \leq {} & (p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}-1} + p^{\text{ramp down}}_{a,y,k_y,b_{k_y}-1} \cdot (p^{\text{duration}}_{b_{k_y}-1} - 1)) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y}-1)} \\
& + (p^{\max}_{a,y,k_y,b_{k_y}-1} - p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}-1} - p^{\text{ramp down}}_{a,y,k_y,b_{k_y}-1} \cdot (p^{\text{duration}}_{b_{k_y}-1} - 1)) \cdot v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \\
& \forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y} \setminus \{b^{\text{start}}\}
\end{aligned} \tag{4}
$$

The second tight constraint, shown above in inequality (4), limits the outgoing flow of generators of type a, as related to the shut-down capability and ramp-down limit of the asset. The structure is similar to inequality (3), but instead, the ramp down rate and shut-down capabilities are the limiting factors of the asset's production. This can be viewed as the limit of the asset's maximal production level at time step $b_{k_y}-1$, at which it can start its shut-down sequence and ultimately be turned off at the subsequent time step b_{k_y}.

The constraints presented in this section are combined together to model both the start-up and shut-down capabilities of generators. To accurately describe the SU/SD capabilities of generators, all four formulations will be included at once. One practicality that arises from the use of the min formulation in (3) is that the constraint creation can be skipped altogether in the case that $p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} + p^{\text{ramp up}}_{a,y,k_y,b_{k_y}} \cdot (p^{\text{duration}}_{b_{k_y}} - 1) > p^{\max}_{a,y,k_y,b_{k_y}}$ (SU/SD capability larger than maximal production, causing a redundant constraint), as this is known in advance from the model parameters. This is included in the model via an *if*-statement.

3 Experimental Setup and Results

This section describes the experiments that were ran to find the effects of including start-up and shut-down ramping constraints in the Tulipa model. Section 3.1 describes what data was used to build the case studies used in testing, while Section 3.2 describes how experiments were structured, and what metrics and methods were used to measure the differences in results. Finally, section 3.3 describes the results of the experiments.

3.1 Case Studies

The case study used in the research is a model of the European energy grid, consisting of 30 countries, each with a set electricity demand profile. Of these 30 countries, 27 are European Union member states, and the three remaining nations are Norway, Switzerland and the UK. The choice of countries is based on the test case presented in [12], therein referred to as "EU+3". Each country has its own distribution of electricity demand in time, per representative period, and the distribution of renewable energy generation potential in time; the latter can be thought of as the the strength of available wind and sunshine, per hour and representative period. These are known as the demand profiles, and availability profiles, respectively. The countries have an option for international grid connections, allowing for a limited amount of electricity trade; this case is optional to the system analysis, and included as a supplement in Appendix A. The core motivation behind the creation of this case study is to create a large system with non-homogeneous demand across countries, as large test cases are expected to show the biggest differences when temporal reductions are employed, especially given the NP-Hard nature of MILP problems. The demand profiles for each country were taken from [12], while the availability profiles for IRES were supplied via personal communication with the Tulipa team at TNO [22].

To model Generation Expansion Planning with Unit Commitment, each country in the case study starts with zero initial electricity sources, and may invest into integer amounts of generators of seven different technologies, each modelled to have a specific set of UC parameters. These technologies include solar generators, onshore and offshore wind turbines, nuclear power plants, combined-cycle and open-cycle gas turbines, and coal power plants. Each technology of generators has a defined capacity, i.e. the generator's maximum production limit. To keep capacities plausible and in the realistic generator capacity range, the average capacity per main fuel type for generators globally [23] was taken. Only generators with a single fuel type were considered, such that capacities are not affected by inclusion of secondary fuels. Finally, the model includes the option to invest into batteries as a storage technology; given that battery arrays can be expanded in a more flexible manner, and in a bid to reduce the computational burden of the computation, these can be invested into in non-integer amounts.

The ramp up/down limits of generators were based on data used in [24], for all but the Nuclear plants, as they do not exist in the dataset. Ramping rate for Nuclear plants was taken from [25], and assumed the same for ramp-up and ramp-down. The SU/SD capability parameters, and minimal operating point (minimal stable production level) data were also taken from [25]. The cost of constructing a generator of each technology, herein referred to as the Investment Cost, was taken from [26]. This Investment Cost is defined per unit of the generator's capacity, i.e. the final cost is a product of installed capacity and the reported Investment Cost. The cost of electricity production for thermal generators, in currency per MWh, is based on real data compiled in [27, 28, 29]. The summary of the generators' specifications for each of the seven technologies is presented in Table 1. Note that renewable generation technologies are missing Unit Commitment data, as UC is only applied to thermal generators. Finally, the cost for investment into battery capacity was also taken from [26], and set to 146 $kEUR$ per MWh for storage capacity, and 146 $kEUR$ per MW for the charge/discharge capacity.

3.2 Experimental Setup

The experiments are ran on the scenario described in Section 3.1 at different temporal resolutions, and in two different configurations of UC constraints. The variability of the temporal resolution is done by modelling the system at different fixed temporal resolutions r in the set $r \in \{1, 2, 4\}$ hours, or by modelling resolutions of assets and flows of the EU+3 countries at resolutions that depend on the country's distance from the electrical grid of the Netherlands. The latter is inspired by a similar test case presented in [12], where the resolution depends on the "degree" of the country's grid as compared to the Netherlands, and sets country resolutions as proposed in [12]. The varying of configurations is done by running a model with: only the UC constraints already present in Tulipa, or with the added formulations (1)–(4) presented in Chapter 2. A single combination of a specific temporal resolution and a specific configuration of constraints will be referred to as the *test case* from

Generator	Generator Parameters							
	General Parameters		Production & Investment Costs		Unit Commitment Parameters			
	Capacity (MW)	Minimal Operating Point (100%)	Electricity Production Cost ($\frac{kEUR}{MWh}$)	Investment Cost ($\frac{kEUR}{MW}$)	Maximum Ramp Up (100%)	Maximum Ramp Down (100%)	Maximum Start-Up Ramp (100%)	Maximum Shut-Down Ramp (100%)
Solar	18	0	0	485	No Unit Commitment			
Onshore Wind	49	0	0	1000				
Offshore Wind	49	0	0	2580				
Nuclear	2095	0.5	0.0084	5658	0.3	0.3	0.5	0.5
Combined-Cycle Gas	357	0.45	0.033	775	1	1	0.45	0.45
Open-Cycle Gas	357	0.2	0.051	475	1	1	0.2	0.2
Coal	824	0.325	0.0177	1500	0.5	0.5	0.38	0.38

Table 1: Operational parameters per generation technology, with investment and energy production costs.

hereafter. Test cases presented in this section do not consider trade between countries, and cases with trade are presented in Appendix A.

There are four main measurements of the effect of the constraints on the model. These are the **Run and Creation Times**, the **Objective Function** differences, the **Investments** into technologies, and the **Metrics for UC Capabilities**. These are described in more detail in Table 2.

Measurement	Description
Run and Creation Time	Time required to solve the model, affected by number of solver iterations, which may increase as the result of more partitioning necessary given the introduction of SU/SD constraints. Creation time affected by the extension of creation logic to include additional steps and SQL queries. Mean and Standard Deviation reported, over 20 trials, with random solver seed.
Objective Function	Total cost of the system, affected by choice of purchased generators and fuel costs given production from various sources. Introduction of SU/SD constraints may favour generator technologies with different capabilities, affecting choice of purchased generators and power production, indirectly affecting costs. Measured in Euro for seed=0.
Investments	Investments into generators, in MW. Inclusion of SU/SD capabilities may favour specific generators, causing a difference in investments. Determined for seed=0.
Metrics for UC Capabilities	Includes custom metric of unit-on-hours, describing the number of hours at which generators are committed (online). Aims to describe how long generators must be kept online, as reduced SU/SD capabilities may require generators to start-up sooner and shut-down later to meet required ramping capability. Determined for seed=0.

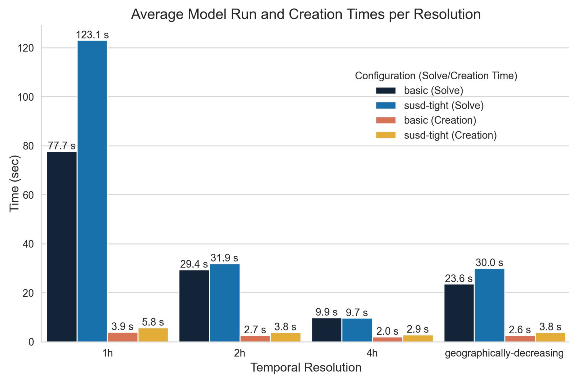
Table 2: Experimental metrics, with descriptions and motivation.

To run the experiments, the Tulipa Energy Model [14] version 0.15.1 was extended with the proposed constraints. Gurobi version 12.0.2 was used as the solver, with the MIP Gap set to 0.01%. The tests were ran on a virtual machine with dedicated 16 CPU cores of AMD EPYC 9R14 with SMT disabled, with max clock of 3.7Ghz and with 32 GB of RAM.

3.3 Numerical Results

This section introduces the results of running the test cases described in Section 3.1, using the metrics from Section 3.2. The focus of this section is mainly to provide the results of tests, while the discussion is left for Chapter 4.

Run & Creation Times With the added constraints, the model requires a significantly longer time to solve in the case of the hourly temporal resolution, and sees a moderate solver time increase in the geographically-decreasing case. Lesser difference is seen for the 2h resolution, while the run time difference between the 4h cases is insignificant ($< 1 \cdot \sigma_{4h}$). All test cases see an increase in the time required to create the model with constraints as compared to without them, with the biggest absolute difference seen between the cases with hourly resolution (1.86s). In general, the time required to create the model decreases as the temporal resolution is reduced; a similar pattern appears for the time required to solve the model, yet the difference in solve time follows an approximately exponential pattern. Model run and creation times have been summarised in Fig. 2.



(a) Mean Run & Creation Times

Resolution	Configuration	Run Time		Creation Time	
		Mean	St. dev.	Mean	St. dev.
1h	Basic	77.75	2.53	3.93	0.10
	SU/SD + Tight	123.09	6.11	5.79	0.15
2h	Basic	29.43	1.93	2.66	0.08
	SU/SD + Tight	31.91	1.81	3.80	0.11
4h	Basic	9.87	0.68	2.05	0.05
	SU/SD + Tight	9.68	0.56	2.86	0.07
Geographic. Decreasing	Basic	23.62	1.06	2.65	0.09
	SU/SD + Tight	30.04	1.22	3.81	0.07

(b) Run and Creation Time means and standard deviations. $n = 20$ samples.

Figure 2: Run and Creation Times statistics per Temporal Resolution. Configuration "Basic" refers to the model with only the existing UC formulations in Tulipa, while "SU/SD + Tight" refers to a model with additional formulations (1)–(4), presented in Section 2.

Investments The choice of optimal investments, summarized in Fig. 3, changes little across test cases, with minimal differences between test cases at the same temporal resolution. In general, there exists a persistent pattern of primary investments carried out in the renewable power group, and no investments being made into Nuclear or Offshore Wind generators; the latter are not reported for conciseness. The influence of the SU/SD capabilities on the investment plan is minimal. Overall, the largest relative difference is found for Batteries, where models with increasingly fine temporal resolutions invest into larger battery capacities ($>$ 25X increase between 4h basic and 1h basic test cases). Moreover, battery investments are slightly larger for all SU/SD cases when compared to the Basic cases, irrespective of the resolution. When considering the invested capacities for the Netherlands specifically, summarized in Table 3, the inclusion of the SU/SD capabilities has no effect on the purchased capacities of thermal generators at the 1h and geographically-decreasing resolutions. The only differences at these resolutions for NL can be seen for Solar and Battery investments, with either one of the technologies seeing a small ($<$100MW) increase in investments when SU/SD capabilities are added.

Following the little change in generation capacity, the total electricity production by source did not change significantly either. In the 1h case, the introduction of SU/SD constraints reduced electricity generation from thermal generators by 166.7 GWh, with renewable energy sources taking over this electricity demand.

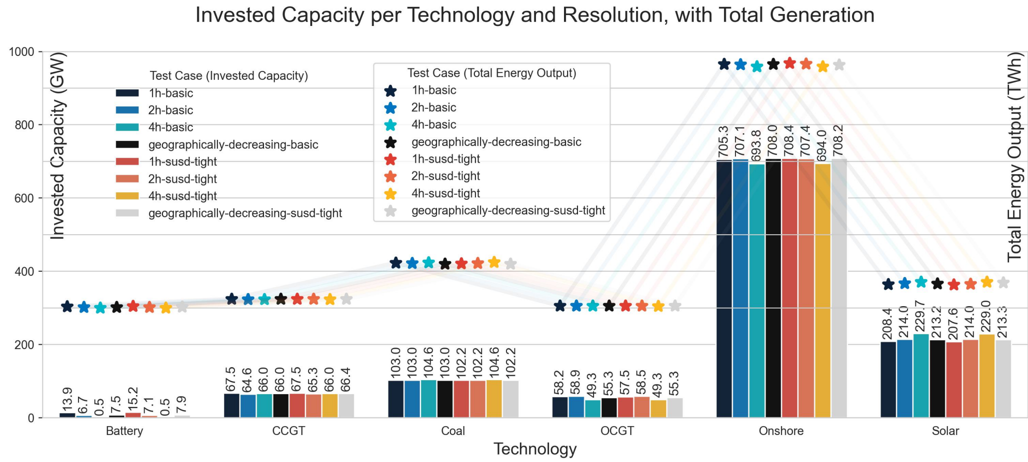


Figure 3: Total investments into assets in GW, and energy output in TWh, grouped by generator type, for different temporal resolutions and configurations. The bar chart depicts the investments, while the star-shaped points depict the energy output.

Resolution	Configuration	CCGT	Coal	OCGT	Onshore Wind	Solar	Battery
1h	Basic	2499	4120	1785	25088	8190	59.29
	SU/SD Tight	2499	4120	1785	25039	7992	82.36
Geo-decreasing	Basic	2499	4120	1785	25088	8154	60.97
	SU/SD Tight	2499	4120	1785	25088	8226	57.78

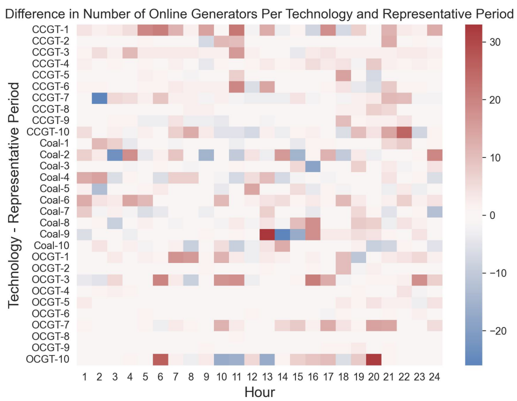
Table 3: Investment into generators per type in MW, in NL only, for 1h and geographically-decreasing temporal resolutions, across configurations.

Objective Function The value of the objective function for the whole of EU+3, listed for several test cases in Table 4, sees only small differences when SU/SD capabilities are added to the model. Between the test cases at 1h resolution, the inclusion of SU/SD capabilities increases the total cost by approx. 0.036%, just above 3.5X the MIP Gap. All other test cases see a decrease in the value of the objective, with this difference enlarging as the resolution becomes less fine. When cost for the Netherlands only is considered, both 1h cases and the geographically-decreasing cases show a small cost increase when the SU/SD capabilities are added, while otherwise a much larger cost decrease is seen.

Type	**Configuration**	**1h**		**2h**		**4h**		**Geo-Decreasing**	
EU+3	Basic UC	63.030	-	62.823	-0.3287%	62.278	-1.192%	62.708	-0.5105%
	SU/SD + Tight	63.053	+0.0366%	62.823	-0.3282%	62.277	-1.194%	62.714	-0.5015%
NL Only	Basic UC	2.2226	-	2.2117	-0.4913%	2.2046	-0.8125%	2.2227	+0.0034%
	SU/SD + Tight	2.2231	+0.0189%	2.2117	-0.4913%	2.2046	-0.8125%	2.2235	+0.0376%

Table 4: Objective Function value in Billions of Euro, and its relative difference across configurations, temporal resolutions and cases.

UC Metrics The inclusion of the new SUSD capabilities appears to lead to a noticeable increase in the number of generators that are committed throughout the ten representative periods that are modelled. Figure 4a provides a visual overview of the difference of the number of committed generators between the scenario with SU/SD capabilities and without, for thermal technology types across the modelled time. The general increase in the number of unit-hours is shown in Table 4b (top), where it can be seen that the inclusion of the SU/SD capabilities at hourly resolution causes a consistent increase in the number of unit-hours between generators of a specific technology. Similarly, including SU/SD capabilities in the geographically-decreasing scenario also sees a consistent increase in the number of unit-hours on. Other test cases see a trade-off between larger commitment of some technologies, and lesser of others. In total, largest increases in the number of unit-hours appear for the 1h and geographically-decreasing cases, as shown in Table 4b (bottom).



(a) Difference in number of committed generators per representative period, between Basic and SU/SD+Tight configuration.

Configuration	Case	CCGT		Coal		OCGT	
1h	Basic	7892	-	18306	-	2287	-
	SUSD Tight	8320	+5.42%	18443	+0.75%	2623	+14.69%
2h	Basic	7640	-3.19%	18092	-1.17%	2762	+20.77%
	SUSD Tight	7760	-1.67%	18252	-0.29%	2762	+20.77%
4h	Basic	7632	-3.29%	18648	+1.87%	2344	+2.49%
	SUSD Tight	7580	-3.95%	18692	+2.11%	2328	+1.79%
Geographically Decreasing	Basic	7604	-3.65%	18301	-0.03%	2355	+2.97%
	SUSD Tight	8016	+1.57%	18507	+1.10%	2429	+6.21%

Configuration	1h	2h	4h	Geo-Decreasing
Basic	-	+ 9	+ 139	- 225
SUSD Tight	+ 901	+ 289	+ 115	+ 467

(b) Difference in number of unit-hours of enabled generators, per type, configuration and resolution (top), aggregated over types (bottom)

Figure 4: Difference in commitment status of generators in scenarios using only basic UC capabilities, and SU/SD+Tight capabilities. Warmer colours (red) represent a relative increase, while cooler colours (blue) represent a relative decrease.

4 Discussion

The effects of varying the constraint configuration and the temporal resolution, on the model's run and creation times, optimal investments, the total cost of the system and the short term operational characteristics of generators have been described in Section 3.3. This section examines these results and provides summaries and explanations for the observations.

The model sees an approximately exponential increase in time required to solve it as the temporal resolution becomes increasingly fine, and the inclusion of additional SU/SD constraints further increases this time, by up to 58.3% for the 1h case (Figure 2b). The lesser increase in solve time for the remaining resolutions can be explained by the restriction of the SU/SD capabilities to only exist for cases where the generator's SU/SD ramping limit across a time block does not exceed maximal power output. Given the parameters shown in Table 1, for lower temporal resolutions (2h+), certain generators such as CCGTs and OCGTs no longer satisfy this condition. As a result, the 2h temporal resolution sees only a small difference in solve time, as effectively only the Coal generators include the SU/SD capability constraints, and do so with a high limit that is relatively easy to satisfy. At 4h resolution, in practice, all SU/SD constraints are lifted, explaining why the difference between configurations is smaller than the standard deviation. The geographically-decreasing resolution contains a mix of countries modelled at 1h to 5h resolutions, which is why the relative difference between constraint configurations there falls between that of the 1h and the 2h resolutions. These observations serve to validate that the increase in run-time behaves in a predictable manner across the varied temporal resolutions. Finally, the creation time of the model increases slightly for finer temporal resolutions and for cases with extra constraints; however, the absolute difference is relatively small, on the order of seconds. This difference is largely owing to the fact that additional logic for creating the SU/SD constraints performs an extra number of simple iterations during model creation, proportional to the model size.

Following the little difference in the optimal system costs, and the investments, between cases of the same temporal resolution seen in Section 3.3, it is summarized that the inclusion of extra UC capabilities has little effect on generation expansion planning in the cases explored in this research. In an attempt to place the findings in a broader context, it must be noted that in [10] it was found that inclusion of UC constraints into GEP for systems with large amount of flexibility provided by sources other than thermal generators causes little difference in system costs and investments into thermal generators. It is hypothesized that a similar situation is happening for our system, where the addition of extra SU/SD capabilities on top of the existing model produces little effect, as the system is already highly flexible owing to the enabled investments into energy storage (Batteries), which allow quick power delivery that covers the fluctuations of the grid. The large relative difference for invested capacity into batteries between temporal resolutions, shown in Section 3.3, is most likely due to a steadier IRES production at lower resolutions, as flow does not change as quickly, reducing the need for battery supply required to handle sudden power differences.

When the change in system cost and investments is analysed against the run (solve) times of the model, a trade-off between computation time, and accuracy of the model with respect to the 1h resolution, becomes apparent. The decrease in temporal resolution is associated with both a lower run time, and a larger percentage difference in total system costs. Moreover, the decrease of temporal resolution correlates with larger investment differences, especially for Batteries and Solar generators. Reduced resolution cost differences are much larger than those between the inclusion and exclusion of the SU/SD capabilities, and thus signify that the temporal resolution has a much larger effect on model solutions. However, when the same trade-off is analysed for the Netherlands only, it can be seen that the geographically-decreasing temporal resolution shows very little change in costs for NL as compared to the 1h resolution (Table 4). This follows from the modelling choices, as the assets in the Netherlands are modelled at hourly resolution, thus similar optimal solutions are expected in a case study without trade. The results shown in [12], where geographically-decreasing temporal resolution with trade, centered on the Netherlands, was considered, also show the error in investments in the Netherlands to remain small, albeit involving an enlarged error for the remainder of EU+3. Despite the lack of trade in our case study, NL at the geographically-decreasing resolution displays a similar trend, signifying a possibility of reducing the time required to solve the model, at a small error for a selected country.

While little difference was found for total costs and the investments, the operational schedule for thermal generators changes between the cases that model SU/SD capabilities, and those that do not. As shown in Section 3.3, the thermal generators operate for more unit-hours in the case with limited SU/SD capabilities. This difference in commitment can be explained by generators possibly having to start up one time block earlier, beginning their ramping at an earlier point to be able to satisfy the demand, possibly in conditions where IRES availability is reduced. Similarly, the generators may need one more time block to ramp down their production and shut down completely, and thus the time between the generator start-up and shut-down may increase slightly.

Responsible Research

This section describes the measures taken to promote a responsible research process. The section will describe how data is open and available for research, explain why the results are reproducible, and discuss the integrity of the study.

The experiments presented in this paper rely largely on openly available data taken from existing research and official sources. Data supplied by personal communication was used where necessary, yet publicly-available data was preferred and chosen where possible. To promote reproducibility and research transparency, all input data used to create the experiments, as well as the output data that was analysed in this paper, is made available on a public repository [30]. The input data is saved in a CSV file format compatible with Tulipa version 0.15.1, and given that the CSV format is widely supported, and columns are annotated, it can be adapted to other formats and interoperate with other software.

All presented results, with the exception of the run and creation times of the model, were obtained from experiments ran using a deterministic setting of Gurobi, with seed set to 0. This choice was made to promote reproducibility of the research, as a deterministic seed should lead to consistent solutions, provided that the data, the parameters and other solver settings remain the same. However, Run and Creation times may differ for two reasons: 1. the hardware on which the model is ran, as well as the operating system's current workload, may cause significant differences in the time required to complete the operations, and 2. the tests were ran on multiple, randomly-generated seeds, to capture an expected average case of run-time for a given test case, regardless of what state the solver starts from. These two reasons make it possible for the run and creation times to differ.

The Tulipa Energy Model used for this research is available under an Apache 2.0 License, providing an open-source software package that can be used in future research, promoting reproducibility. The solver used for the research, Gurobi 12.0.2, is not available open-source, yet can be obtained free of charge via an academic licence. Moreover, the Tulipa Energy Model is compatible with other solvers such as HiGHS, which can be used as an open-source alternative to Gurobi under an MIT license. However, it is important to note that the choice of solver impacts the time required to solve the model significantly.

To uphold research integrity, the sources of the data used for experiments, as well as the model and solver software have been cited. All text within this paper was written manually, without the use of Generative AI. Care was given to report the results without a preference to findings that support or contradict the usefulness of the constraints whose impact is being investigated. Finally, the code used to create the constraints is available on a public repository [31], allowing validation of the results presented in this paper.

5 Conclusions and Future Work

The paper introduced four new Start-Up and Shut-Down (SU/SD) capability constraints designed to work at a fully flexible temporal resolution, and evaluated their effect on the runtime of the model, the model's optimal cost, investments and the commitment of generators using a test study modelled after the European energy grid (EU+3). It was found that the inclusion of the SU/SD capabilities is associated with an increase in time required to solve the model, with this difference scaling up as temporal resolution is increased. Difference in system cost as the result of introducing SU/SD capabilities was found to be minimal, and in practice much larger differences were found when the temporal resolution alone was varied. Similarly, the model's investment plan was found to react little to the introduction of

SU/SD capabilities alone, with significantly larger differences seen when just the temporal resolution is varied. However, the choice to model a specific country, in the case of this research – the Netherlands, at a higher temporal resolution, while reducing resolutions elsewhere, introduced little error for that country alone, while significantly decreasing run time, signifying a possible method of managing model size. Finally, the inclusion of the SU/SD capabilities was found to impact the commitment of generators in a significant manner, on average increasing the time for which generators are committed.

As a result, the current findings suggest that the inclusion of the SU/SD capabilities may be omitted from GEP modelling if the system has a large supply of flexibility providers, such as Battery Energy Storage Systems (BESS) for cases where only the investments and cost are of paramount importance. In such systems, the SU/SD capabilities may be considered for cases where short term operations or the UC schedule are of significant importance. The trade-off between model accuracy and computation time suggests that omitting the constraints and increasing the resolution of the model is the preferred choice when available run time is limited. The adaptation of the capabilities to work with fully flexible temporal resolutions opens the possibility for reducing the run time of large models, especially in cases where the accuracy of a selected country is of higher importance than of the whole system.

The study was conducted on a model with ten representative periods, yet an attempt was made to compare the results against a full-year model. However, given the limitations of available compute power and time, a full-year case study never successfully computed, even when simple temporal resolution reductions were introduced. Future work could address this issue, possibly by studying a smaller model that introduces SU/SD capabilities, especially in the areas of run time and the impact on investments. A full-year model with non-uniform temporal resolution, such as triweekly blocks, where the first week is modelled at 1h resolution, and the two other at reduced 4h resolution, could be a particularly interesting alternative to using representative periods. Moreover, future work could compare the results presented in this paper against similar capability formulations that instead use dedicated start-up and shut-down variables.

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A EU Case Study With Investable Trade

This appendix presents a supplementary case study that includes investable trade between countries, along with a more complex example of a fully flexible temporal resolution. Section A.1 covers the differences as compared to the case studies presented in the main body of the paper, and Section A.2 introduces the numerical results for the system. Finally, Section A.3 discusses the results.

A.1 Experimental Setup

The case study used for the experiments that involve investable trade remains similar to that presented in Section 3.2. The largest differences between the two case studies are the enabled investments into international energy trade, as well as the choice of different temporal resolutions for the EU+3 countries in the system. Preliminary testing showed much longer run-times, and the choice was made to lower the MIP Gap to 0.1% to fit within available time. Finally, the run times were evaluated using fifteen samples, over the course of two separate runs, as compared to the twenty samples reported in the main body of the paper.

The model now provides an option for the purchase of a 1GW connection between countries of EU+3, where this connection exists and is investable for countries as modelled in [12]. The inter-country connections are modelled to have a 90% efficiency, and the flow between countries is considered to be free once the connection is purchased. The reason for the latter choice is that the overall objective of the model is the cost of the EU+3 system, rather than an individual country's energy grid cost, and as such, the financial transactions that could accompany energy trade are not modelled. The reason for limiting the trade link investments to a maximum of 1 GW between countries is to disallow the model from purchasing all generators of a given type in one area of EU+3, promoting a more realistic case where countries' grids must be at least partially independent from other EU+3 countries. The choice of grid interlink connection was left to be binary (0 or 1GW), to reduce the search space, and given that preliminary testing and experiments showed little difference in link investments between the option of a binary connection investment decision, and an integer decision with a 250MW investment step.

Resolution		Countries
Flow	UC	
1h	1h	Netherlands, Belgium, Germany, United Kingdom, Denmark, Norway
1h	2h	France, Luxembourg, Switzerland, Ireland, Sweden, Austria, Czech Republic, Poland
2h	3h	Spain, Italy, Lithuania, Finland, Slovenia, Hungary, Slovakia
3h	4h	Portugal, Croatia, Romania, Greece, Latvia, Estonia, Malta, Cyprus
5h	5h	Bulgaria

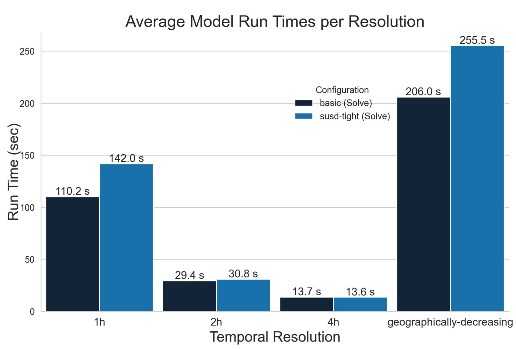
Table 5: Fully Flexible Temporal Resolutions for Flow and Asset Commitment in the Geographically-Decreasing case with trade.

The temporal resolution of countries within the model considered in the test cases presented in this Appendix are either uniform temporal resolutions $r \in 1, 2, 4$, as in the main body of the paper, or custom temporal resolutions that are increasingly lower for countries whose electrical grid is more distant to that of the Netherlands, but the latter are not necessarily the same for assets and flows of a given country. The applied resolutions for country flows and generator commitment are depicted in Table 5. Flows between two countries are modelled at the higher of the two resolutions. The choice of resolutions was such that the resolution of flow is greater or equal that of the commitment of the asset, though in general, the chosen resolutions serve less as a realistic model, and more as a benchmark that involves fully flexible temporal resolutions that do not match up between the UC and Flow variables. This resolution will still be referred to as a geographically-decreasing temporal resolution in the experiments described in the Appendix, given that the resolution does decrease for countries that are farther from the Netherlands.

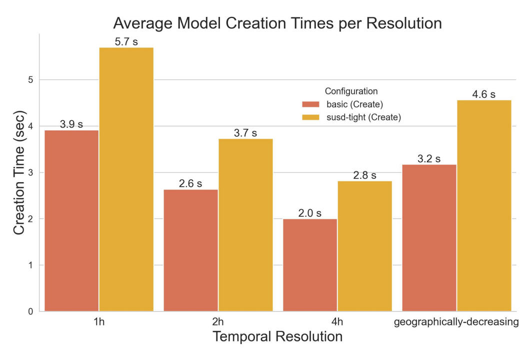
A.2 Numerical Results

This section presents the numerical results from experiments ran on the model, and discussion is left for Section A.3.

Run Times The model sees a moderate increase in time required to solve it when the SU/SD capabilities are included in test cases at 1h and geographically-decreasing temporal resolutions. Little difference in run time between the two constraint configurations is seen for the 2h and 4h resolutions. All of the test cases with enabled investments into trade connections ran for a similar or longer time when compared to the no-trade test cases whose results were presented in Section 3.3, despite the reduced MIP Gap of 0.1% for the case study in this appendix. Moreover, the geographically-decreasing fully flexible temporal resolution runs here for the longest time, with >79% solve time increase over the 1h resolution for both configurations, which is opposite of the results presented in Section 3.3, where the geographically-decreasing resolution test cases ran significantly faster than the test cases at 1h resolution. The run times can be seen in Figure 5a.



(a) Average Model Run Times for cases with enabled investments into trade per test case.



(b) Average Model Creation Times for cases with enabled investments into trade

Figure 5: Run and Creation Times for the model with enabled investments into electrical connections between countries.

Creation Times The time required to create the model sees an increase for the SU/SD-Tight configuration over the Basic configuration for every temporal resolution, with the creation time scaling up as the resolution becomes more detailed. However, it must be noted that differences in run time between different seeds were significant, with up to 79.06s standard deviation in the geographically-decreasing case with SU/SD capabilities, possibly as a result of the large MIP Gap. All creation times are higher for the case with trade as compared to the results presented in Section 3.3, although this difference is relatively low. The increase in creation time displays a trend similar to the increase shown in Section 3.3. The creation times have been depicted Figure 5b.

Investments The investments into technologies follow the same general trend as shown in Section 3.3, with primary investments into renewable energy sources, as can be seen in Figure 6. However, when the investments of the model with trade are compared to the model without trade, the latter presented in Section 3.3, fewer investments are made into thermal generators, with the largest relative difference seen for OCGT and CCGT generators. When the configurations with the SU/SD capabilities and without are compared, little difference in investments is seen. Similarly to the results found for the model without trade, the temporal resolution appears to have a much larger effect on the invested capacities, especially for Batteries, and for Solar at 4h temporal resolution. Table 6 shows that the invested asset capacities, for the Netherlands only, differ the most for OCGTs, with 1 to 3 generators bought for each test case, and Batteries, with only the 1h Basic test case purchasing them. At the same time, the investments for the Netherlands never include Solar generators or Batteries for the two resolutions and the configurations.

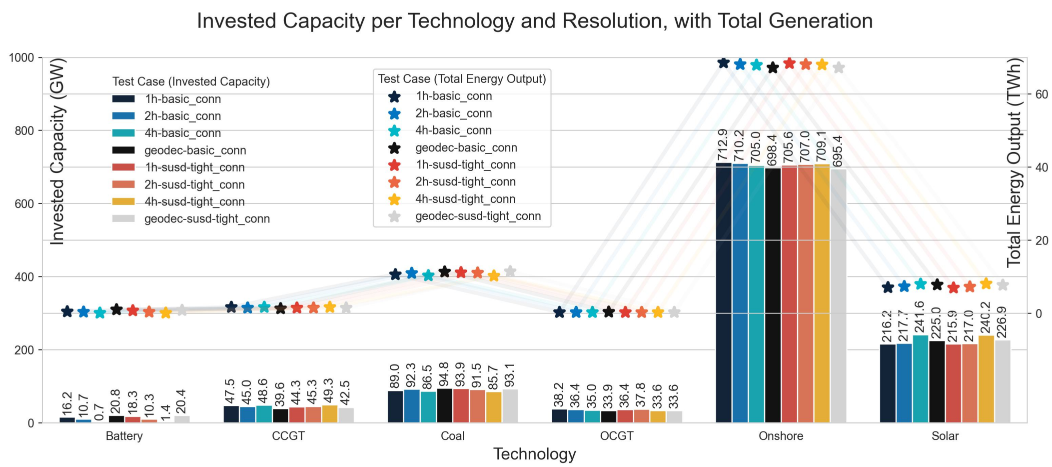


Figure 6: Investments into capacity of assets, in GW, and total energy output in TWh, per technology type and test case. The bar chart depicts the investments, while the star-shaped points depict the energy output.

Resolution	Configuration	CCGT	Coal	OCGT	Onshore Wind	Solar	Battery
1h	Basic	3927	4120	714	25382	0	329.32
	SU/SD Tight	3213	4944	714	25431	0	0
Geo-decreasing	Basic	3213	4944	0	24941	0	5.01
	SU/SD Tight	3213	4944	357	25088	0	0

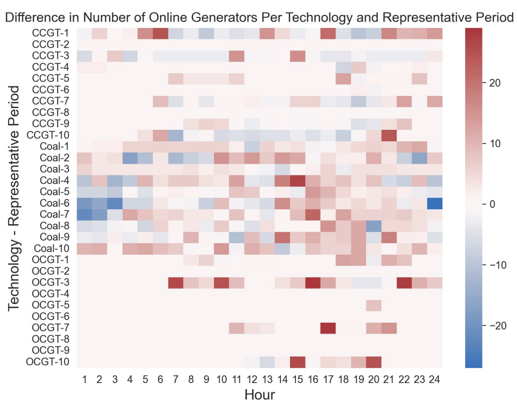
Table 6: Investment Capacities in the Netherlands (MW), at 1h and geographically-decreasing temporal resolutions, in case study with allowed investment into inter-country connections.

Objective Function As can be seen in Table 7, the biggest cost increase for the system as a whole can be found at 1h resolutions, when the SU/SD capabilities are introduced.

However, the difference (0.088%) falls below the MIP Gap of 0.10%, and therefore the increase is not significant. For all resolutions in the NL-Only cost, the inclusion of SU/SD capabilities has a larger cost as compared to the Basic configuration. However, it must be noted that the cost of the Netherlands corresponds to approximately 3.5% of the total system cost, thus any NL cost difference has a much lesser impact on the final objective. All test cases at non-1h resolution see a decrese for the overall (EU) system cost, and NL-Only cost only sees an increase at 1h and geographically-decreasing resolutions, and a decrease elsewhere.

Type	**Configuration**	**1h**		**2h**		**4h**		**Geo-Decreasing**	
EU+3	Basic UC	59.041	-	58.895	-0.247%	58.344	-1.181%	58.869	-0.291%
	SU/SD + Tight	59.093	+0.088%	58.887	-0.261%	58.339	-1.189%	58.878	-0.276%
NL Only	Basic UC	2.1251	-	2.1069	-0.857%	2.0713	-2.529%	2.1138	-0.531%
	SU/SD + Tight	2.1652	+1.886%	2.1152	-0.463%	2.1002	-1.169%	2.1255	+0.022%

Table 7: Total system cost difference across temporal resolutions and configurations, for the case study with international flows that can be purchased. Row "EU+3" specifies the total cost of the EU+3 countries, while row "NL Only" specifies the cost for the Netherlands alone.



(a) Difference in number of committed generators per representative period, between Basic and SU/SD+Tight configuration at 1h res.

Configuration	**Case**	**CCGT**		**Coal**		**OCGT**	
1h	Basic	4664	-	14853	-	864	-
	SUSD Tight	4799	+2.89%	15384	+3.58%	1225	+41.78%
2h	Basic	4250	-8.88%	13612	-8.36%	832	-3.70%
	SUSD Tight	4360	-6.52%	15004	+1.02%	876	+1.39%
4h	Basic	4808	+3.09%	13468	-9.32%	836	-3.24%
	SUSD Tight	4768	+2.23%	14500	-2.38%	736	-14.81%
Geographically Decreasing	Basic	3983	-14.60%	16092	+8.34%	1111	+28.59%
	SUSD Tight	4723	+1.27%	16126	+8.57%	1259	+45.72%

Configuration	**1h**	**2h**	**4h**	**Geo-Decrease**
Basic	-	- 1687	- 1269	+ 805
SUSD Tight	+ 1027	- 141	- 377	+ 1727

(b) Difference in number of unit-hours of enabled generators, per type, configuration and resolution (top), aggregated over types (bottom)

Figure 7: Difference in commitment status of generators in scenarios using only basic UC capabilities, and SU/SD+Tight capabilities. Warmer colours (red) represent a relative increase, while cooler colours (blue) represent a relative decrease.

UC Metrics The inclusion of SU/SD capabilities is associated with a significant increase in the number of hours at which units stay online, as can be seen in Fig. 7b (bottom), although the metric also increases for the Basic configuration as the resolution is reduced. From figure 7b (top), it can be seen that the largest relative differences appear for CCGT and OCGT generators, in the test case at hourly resolution with SU/SD capabilities, as well as in the geographically-decreasing test case with SU/SD capabilities. Finally, Figure 7a shows that the inclusion of SU/SD capabilities impacts the operational schedule of the generators in a non-uniform manner, with the CCGT and OCGT generator differences forming horizontal patterns that showcase that the difference persists through several consecutive time blocks.

A.3 Discussion

This appendix presented a case study that introduced investable inter-country connections, and examined the impact of the inclusion of the SU/SD capabilities on the model's run and creation times, the optimal investments, the total cost of the system and the short-term operational characteristics within the system. While similar input data was used for the case study presented here, compared to the main study in the paper, large differences are seen in the numerical results of the the model's run time, cost and investments.

The time required to solve the model is greater or equal for all test cases when compared to the case study without electrical trade, despite the lowered 0.1% MIP Gap. This is not an unexpected result, as the inclusion of optional energy trade, along with variables for trade investments, increases the search space that the solver must find optimal solutions in. The uniform temporal resolutions display the same trend of decreased resolutions correlating with reduced solve times, though this trend no longer holds for the geographically-decreasing resolution. The latter runs for the longest of test cases of any temporal resolutions, despite having fewer UC and Flow variables as compared to the 1h resolution test case. It must be noted that this is an unexpected result, as the apparent decrease in solution space combined with the non-increase of the number of constraints was expected to decrease the run time when compared against the 1h resolution.

The main differences between the geographically-decreasing test cases presented in this Appendix, and those in Section 3.1, are the inclusion of inter-country trade, the use of mixed UC and Flow resolutions, and the reduction of the MIP Gap. The inter-country flow between Lithuania and Latvia was analysed, with the former modelled at 2h flows and the latter at 3h flows, with a 2h in-between link, where it was seen that the flows generally remain unchanged in 6h time blocks (equal to the lower common denominator of the two, $2 \cdot 3$). However, the same was not true for the trade between Romania and Bulgaria (3h, 5h flow resolutions respectively, with a 3h trade link resolution), as the flows for that connection changed more frequently. In the end, it is hypothesized that the introduction of inter-country trade within the case study presented in this paper causes the majority of the geographically-decreasing solve time increase, though it is highly recommended that future work studies such a combination further and in more detail. Ideally, experiments could be ran with more samples and at a lower MIP Gap of 0.01%, to produce more accurate results with a lower standard deviation.

Little difference seen in the investments, and the largely insignificant changes in the total cost of the system are seen in the results. The largest relative difference in investments was seen for Batteries as a response to reducing the temporal resolution, and follows a similar reasoning to that presented in the main body of the paper – IRES production changes less rapidly at reduced temporal resolutions, reducing the need to cater to sudden power spikes. The introduction of SU/SD capabilities alone appears to not have a significant effect on the cost of the model with trade, given that the largest increase in cost for the entire system falls below the 0.1% MIP Gap. The insignificance of the SU/SD capabilities on the model's investments and cost may be attributed to the large amount of flexibility provided by Batteries that can be invested into, as well as the optional trade connections between countries. The latter form an extra source of flexibility, given that trade could be used to balance renewable energy production across countries. It appears that the model already makes use of some of this extra trade flexibility, given that when the model with trade and without are compared, less thermal generator capacity is bought, and the lost capacity is partially replaced with IRES, signifying that the grid interconnection helps with balancing the producion from renewable energy sources.

It is seen that the inclusion of SU/SD capabilities increases the number of hours that generators operate for, and significantly affects the commitment schedule at 1h resolution. However, it must be noted that these results were obtained with 0.1% MIP Gap, which increases the noise in the data, thereby posing a question of whether this reliably remains the case if the MIP Gap is lowered. Following this, future research could investigate the effects of SU/SD capabilities in a model with trade on the commitment schedule using a lower MIP Gap of 0.01%.

Finally, it must be noted that despite the introduction of trade, the model does not necessarily become more realistic or accurate to the real-world conditions. The model's heavy reliance on trade, and especially no investments made into Batteries in the Netherlands for several cases as presented in Table 6, makes it so that the country's grid becomes (partially) dependent on other nations. While the purpose of this paper is not to advise decision-makers or the European energy grid policy, as the paper is focused on technical solutions only, it is important to note that the opinion of whether a scenario with trade is more realistic depends heavily on policy. As such, the modelling choices for real-world conditions may vary heavily from what is presented in this paper, and study of grid expansion policy should be left for dedicated research.

References

[1] Bryan Palmintier and Mort Webster. "Impact of unit commitment constraints on generation expansion planning with renewables". en. In: *2011 IEEE Power and Energy Society General Meeting*. San Diego, CA: IEEE, July 2011, pp. 1–7. DOI: 10.1109/pes.2011.6038963.

[2] Niina Helistö et al. "Including operational aspects in the planning of power systems with large amounts of variable generation: A review of modeling approaches". en. In: *WIREs Energy and Environment* 8.5 (Sept. 2019), e341. ISSN: 2041-8396, 2041-840X. DOI: 10.1002/wene.341.

[3] Clemens Gerbaulet and Casimir Lorenz. *dynELMOD: A dynamic investment and dispatch model for the future European electricity market*. en. Tech. rep. Deutsches Institut für Wirtschaftsforschung (DIW), Berlin, 2017.

[4] Bryan S. Palmintier and Mort D. Webster. "Impact of Operational Flexibility on Electricity Generation Planning With Renewable and Carbon Targets". en. In: *IEEE Transactions on Sustainable Energy* 7.2 (Apr. 2016), pp. 672–684. ISSN: 1949-3029, 1949-3037. DOI: 10.1109/tste.2015.2498640.

[5] Luis Montero, Antonio Bello, and Javier Reneses. "A Review on the Unit Commitment Problem: Approaches, Techniques, and Resolution Methods". en. In: *Energies* 15.4 (Feb. 2022), p. 1296. ISSN: 1996-1073. DOI: 10.3390/en15041296.

[6] Mathias Hermans and Erik Delarue. "Impact of start-up mode on flexible power plant operation and system cost". en. In: *2016 13th International Conference on the European Energy Market (EEM)*. Porto, Portugal: IEEE, June 2016, pp. 1–6. ISBN: 978-1-5090-1298-5. DOI: 10.1109/EEM.2016.7521298.

[7] Morales-Espana, Jesus M. Latorre, and Andres Ramos. "Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem". en. In: *IEEE Transactions on Power Systems* 28.4 (Nov. 2013), pp. 4897–4908. ISSN: 0885-8950, 1558-0679. DOI: 10.1109/TPWRS.2013.2251373.

[8] M. Carrión and J.M. Arroyo. "A computationally efficient mixed-integer linear formulation for the thermal unit commitment problem". In: *IEEE Transactions on Power Systems* 21.3 (2006), pp. 1371–1378. DOI: 10.1109/TPWRS.2006.876672.

[9] Rogier Hans Wuijts, Marjan Van Den Akker, and Machteld Van Den Broek. "Effect of modelling choices in the unit commitment problem". en. In: *Energy Systems* 15.1 (Feb. 2024), pp. 1–63. ISSN: 1868-3967, 1868-3975. DOI: 10.1007/s12667-023-00564-5.

[10] Kris Poncelet, Erik Delarue, and William D'haeseleer. "Unit commitment constraints in long-term planning models: Relevance, pitfalls and the role of assumptions on flexibility". en. In: *Applied Energy* 258 (Jan. 2020), p. 113843. ISSN: 03062619. DOI: 10.1016/j.apenergy.2019.113843.

[11] Maren Ihlemann et al. "SpineOpt: A flexible open-source energy system modelling framework". en. In: *Energy Strategy Reviews* 43 (Sept. 2022), p. 100902. ISSN: 2211467X. DOI: 10.1016/j.esr.2022.100902.

[12] Zhi Gao et al. *Fully Flexible Temporal Resolution for Energy System Optimization*. en. Apr. 2025. DOI: 10.2139/ssrn.5214263.

[13] Pascale Bendotti, Pierre Fouilhoux, and Cécile Rottner. "On the complexity of the Unit Commitment Problem". en. In: *Annals of Operations Research* 274.1-2 (Mar. 2019), pp. 119–130. ISSN: 0254-5330, 1572-9338. DOI: 10.1007/s10479-018-2827-x.

[14] Abel Soares Siqueira et al. *Tulipa Energy Model*. Apr. 2025. DOI: 10.5281/ZENODO.8363262. URL: https://zenodo.org/doi/10.5281/zenodo.8363262.

[15] Diego A. Tejada-Arango et al. *Tulipa Energy Model: Mathematical Formulation*. en. arXiv:2309.07711. Sept. 2023. DOI: 10.48550/arXiv.2309.07711.

[16] Maaike Elgersma. *Start-Up and Shut-Down Ramping Constraints*. via Personal Communication. 2025.

[17] Pelin Damcı-Kurt et al. "A polyhedral study of production ramping". en. In: *Mathematical Programming* 158.1-2 (July 2016), pp. 175–205. ISSN: 0025-5610, 1436-4646. DOI: 10.1007/s10107-015-0919-9.

[18] Q. Huangfu and J. A. J. Hall. "Parallelizing the dual revised simplex method". en. In: *Mathematical Programming Computation* 10.1 (Mar. 2018). Publisher: Springer Science and Business Media LLC, pp. 119–142. ISSN: 1867-2949, 1867-2957. DOI: 10.1007/s12532-017-0130-5. (Visited on 05/23/2025).

[19] Gurobi Optimization, LLC. *Gurobi Optimizer Reference Manual*. 2024. URL: https://www.gurobi.com.

[20] Jeff Bezanson et al. "Julia: A fresh approach to numerical computing". In: *SIAM Review* 59.1 (2017), pp. 65–98. DOI: 10.1137/141000671.

[21] Miles Lubin et al. "JuMP 1.0: Recent improvements to a modeling language for mathematical optimization". In: *Mathematical Programming Computation* 15 (2023), pp. 581–589. DOI: 10.1007/s12532-023-00239-3.

[22] Diego A. Tejada-Arango. *EU Dataset with Asset Investments*. via Personal Communication. May 2025.

[23] *Global Power Plant Database version 1.3.0*. Global Energy Observatory, Google, KTH Royal Institute of Technology in Stockholm, Enipedia, World Resources Institute. 2021. URL: https://datasets.wri.org/datasets/global-power-plant-database.

[24] Matthias Silbernagl, Matthias Huber, and René Brandenberg. *Improving Accuracy and Efficiency of Start-up Cost Formulations in MIP Unit Commitment by Modeling Power Plant Temperatures*. 2015. arXiv: 1408.2644. URL: https://arxiv.org/src/1408.2644v4/anc/ModelD-2025.xls.

[25] Tom Brown et al. *PyPSA-Eur: An open sector-coupled optimisation model of the European energy system*. Apr. 2025. DOI: 10.5281/zenodo.15163251.

[26] lisazeyen. *PyPSA/technology-data: v0.12.0*. May 2025. DOI: 10.5281/zenodo.15462938.

[27] *Nuclear Power*. Tech. rep. E03. IEA ETSAP, Apr. 2010. URL: https://iea-etsap.org/E-TechDS/PDF/E03-Nuclear-Power-GS-AD-gct_FINAL.pdf.

[28] *Gas-Fired Power*. Tech. rep. E02. IEA ETSAP, Apr. 2010. URL: https://iea-etsap.org/E-TechDS/PDF/E02-gas_fired_power-GS-AD-gct_FINAL.pdf.

[29] *Coal-Fired Power*. Tech. rep. E01. IEA ETSAP, Apr. 2010. URL: https://iea-etsap.org/E-TechDS/PDF/E01-coal-fired-power-GS-AD-gct_FINAL.pdf.

[30] Karol Sperczyński. *Startup and Shutdown Capability Data*. June 2025. URL: https://github.com/kSperczynski/Startup-Shutdown-Capability-Data.

[31] CSE3000 Team 51. *TulipaEnergyModel Fork*. June 2025. URL: https://github.com/Cerberus22/TulipaEnergyModel.jl/tree/startup-shutdown-ramping-constraints.