



Start-Up and Shut-Down Costs in an Energy System Optimisation Model with Fully Flexible Temporal Resolutions

Effect of Adding Start-Up and Shut-Down Costs to the Tulipa Energy Model

Uroš Gluščević¹

Supervisor(s): German Morales-España¹, Maaïke Elgersma¹

¹EEMCS, Delft University of Technology, The Netherlands

A Thesis Submitted to EEMCS Faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering
June 22, 2025

Name of the student: Uroš Gluščević

Final project course: CSE3000 Research Project

Thesis committee: German Morales-España, Maaïke Elgersma, Jérémie Decouchant

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.

Abstract

Fully flexible temporal resolutions have shown to be a useful tool for improving the tradeoff between the runtime and accuracy of generation expansion planning models. However, no research has been done into the effects of considering short-term operational dynamics of thermal generators in models with such resolutions. Therefore, this paper complements the existing literature by adding start-up and shut-down costs to a large-scale energy system optimisation model with a fully flexible temporal resolution. The results suggest that the addition of start-up and shut-down costs significantly increases the runtime of the model, while providing a small increase in accuracy. Additionally, they show that a compact set of start-up and shut-down constraints outperforms a full set of constraints in terms of model runtime, while having the same accuracy.

1 Introduction

Navigating the transition from fossil fuels to renewable energy sources is a challenge which requires governments and network operators to create optimal operation and investment plans for their energy systems. Generation expansion planning (GEP) models, which focus on long-term planning and investments, have been widely used to address this problem [1].

In order to reduce their computational complexity, GEP models have historically ignored short-term operational dynamics related to unit commitment (UC), meaning that they often do not model start-up (SU) and shut-down (SD) costs, among other operational details [2]. However, it has been demonstrated that ignoring UC details, especially those related to unit start-up, can have a negative impact on the accuracy of the model [3, 4]. The reason for this is mainly the increase in penetration of intermittent renewable energy sources, which have an unpredictable power output, as it depends on external factors such as weather conditions [1, 5]. Therefore, in order to provide the flexibility needed to deal with the stochastic nature of intermittent renewable energy sources, generators are required to start up and shut down more often. As a result, it has been suggested that GEP models should take start-up and shut-down costs into account in order to model this behaviour more accurately.

In contrast to GEP models, UC models specifically deal with finding optimal schedules for energy system operation, meaning that they must use the UC constraints often ignored by GEP models. These models have been well explored in recent literature, which is analysed in the literature survey presented in [6].

The survey has identified many trends in approaches to solving the unit commitment problem, but those related to start-up and shut-down costs in mixed integer linear programming (MILP) models are of most interest to this paper. Out of the 70 MILP models surveyed, 64 of them model start-up costs, and 18 additionally model shut-down costs, showing their importance in UC models. The importance of these costs is further exemplified by [1], which states that their inclusion in models is needed to address the need for flexibility resulting from the high penetration of renewable energy sources.

Another observation about UC models is that they predominantly use constant temporal resolutions, meaning that they model time as blocks of constant length. Out of the 70 MILP models analysed in [6], 62 use an hourly resolution, while the others consider sub-hourly time blocks.

However, using an hourly resolution is not suitable for most GEP models, especially those considering longer planning horizons [7]. This is because higher temporal resolutions require more variables and constraints to be included in the model, which can make it

computationally infeasible to solve. One solution to this problem is lowering the temporal resolution, which has the drawback of potentially decreasing the model’s accuracy.

Instead, [8] introduces the idea of a fully flexible temporal resolution. This entails modelling less relevant aspects of the energy system with less temporal detail to reduce computation time, while increasing the resolution of the more important aspects of the system, in order to arrive at a sufficiently accurate solution. One of the examples presented in [8] is the geographically decreasing temporal resolution. It is used to model the energy system of the Netherlands with a resolution of 1 hour, while modelling the other European countries with lower resolutions, the farther away from the Netherlands they are. The preliminary results of the study show that this kind of temporal resolution can decrease the computation time of the GEP model, without introducing high errors in the calculated cost of the Dutch energy system.

However, the GEP model used in the study did not include start-up and shut-down costs and their related constraints. Although the impact of ignoring these costs has been well researched in recent literature, none of those studies have made use of a fully flexible temporal resolution. Therefore, it is not currently known how adding start-up and shut-down costs would impact a model with a fully flexible temporal resolution.

Therefore, the aim of this study is to explore how adding start-up and shut-down costs impacts a GEP model when using a fully flexible temporal resolution, compared to uniform resolutions. Specifically, the focus of the study will be the effects on the model’s computation time, objective function (cost of investments and operation of the system), and investment plan. Multiple experiments will be run, involving constant temporal resolutions, as well as the fully flexible geographically decreasing resolution, for two different sets of start-up and shut-down constraints (full and compact), the results of which will be compared against the model with a uniform hourly resolution and no start-up and shut-down costs.

This paper complements the existing literature in the following ways. Firstly, it shows that the inclusion of start-up and shut-down costs increases the runtime of the model for both uniform and fully flexible temporal resolutions. More importantly, it is shown that the full set of constraints has worse effects on the runtime compared to the compact constraints, for all of the temporal resolutions considered. Secondly, the results of the study indicate that, when considering a geographically decreasing temporal resolution, the addition of start-up and shut-down costs can improve the accuracy of the model. Specifically, when considering the objective function value for the Netherlands, the geographically decreasing model with the compact start-up and shut-down constraints exceeds the Pareto front. However, the paper also shows that the geographically decreasing resolution causes a greater variance in the objective function for the Netherlands, and that the value becomes sensitive to the constraint set used when varying the costs of generator start-up and shut-down. Finally, the results suggest that the geographically decreasing resolution greatly changes the investment plan for the Netherlands compared to the 1-hour uniform resolution. Concretely, it causes the model to invest in a larger amount of battery charge and discharge capacity, while reducing investments into thermal generators when start-up and shut-down costs are added.

The rest of this paper is structured as follows. Firstly, the start-up and shut-down constraints to be added, as well as the additions to the objective function of the model, will be described in Section 2. Section 3 will follow with a description of the setup and result of the experiments. The discussion of the results, along with a reflection of the ethical implications of the study can be found in Section 4. Finally, Section 5 will present the conclusion and suggested further research.

2 Mathematical Formulation

To explore the effects of start-up and shut-down costs on GEP models with fully flexible temporal resolutions, the Tulipa energy model developed by TNO [9, 10, 11] will be used. Tulipa is a GEP model for the electricity market, which can be coupled with other energy sectors, such as natural gas or hydrogen. Other than using flexible temporal resolutions, it also makes use of clustered unit commitment, modelling how many units of a certain type are turned on at a given time.

Being a mixed integer linear programming model, Tulipa aims to find an assignment of variables which minimises an objective function, while satisfying a set of constraints. Version 0.15.0 of the model already includes an objective function comprising of investment, transport, and certain operation costs, which was extended with start-up and shut-down costs as part of this study. Furthermore, two sets of logical constraints related to generator start-up and shut-down were added to the model.

Section 2.1 gives a brief overview of how time is modelled in the Tulipa energy model. Then, Section 2.2 explains Tulipa’s existing objective function, and describes the added start-up and shut-down costs. Finally, the two sets of start-up and shut-down constraints added to Tulipa are explained in Sections 2.3 and 2.4 respectively.

2.1 Overview of the Tulipa Energy Model

The goal of the Tulipa energy model is to find the cheapest investment plan for an energy system which manages to satisfy the energy demand over a set of milestone years, \mathcal{Y} . To reduce its computation time, the model often does not consider every day in a year individually. Instead, it models each year as a set of representative periods, \mathcal{K}_y . These periods are usually days which span different weather and electricity demand profiles, such that they accurately capture the different parts of a year.

In each year $y \in \mathcal{Y}$, the model invests into a set of assets \mathcal{A} , such as wind turbines, solar panels, thermal power plants, and batteries. The model then makes sure that it can satisfy the electricity demand in each of the representative periods, given the specific demand profiles and weather conditions. Some generators, such as coal power plants and gas turbines, also need to satisfy unit commitment constraints, such as ramping limits and minimum operating points. This set of assets is denoted by $\mathcal{A}^{\text{uc}} \subseteq \mathcal{A}$.

Finally, each asset $a \in \mathcal{A}$ can be modelled with a different temporal resolution. This can be achieved by further dividing each representative period into smaller time blocks. For example, the variable $v_{a,k_y}^{\text{units on}}$ represents the number of units of asset a which are operating in the representative period k_y . To model this variable at a resolution of 6 hours, the representative period k_y can be split into 6-hour long time blocks $b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{uc}}$, where $\mathcal{B}_{a,y,k_y}^{\text{uc}}$ is the ordered set $[[1 : 6], [7 : 12], [13 : 18], [19 : 24]]$.

2.2 Start-Up and Shut-Down Costs in the Objective Function

The objective of the Tulipa energy model is to minimise the costs of investing into generators and transmissions, as well as the operational costs of the generators. Currently, the operational costs are modelled as the costs of generating and transporting electricity, as well as fixed and variable costs [10]. In order to include the start-up and shut-down costs, the following quantity is added to the objective function:

$$\sum_{y \in \mathcal{Y}} \sum_{a \in \mathcal{A}_y^{\text{uc}}} \sum_{k_y \in \mathcal{K}_y} \left[\sum_{b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}}} p_{a,y}^{\text{start up costs}} \cdot v_{a,k_y,b_{k_y}}^{\text{start up}} + \sum_{b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{sd}}} p_{a,y}^{\text{shut down costs}} \cdot v_{a,k_y,b_{k_y}}^{\text{shut down}} \right] \quad (1)$$

Equation (1) represents the start-up and shut-down costs incurred by the assets. For each asset $a \in \mathcal{A}^{\text{uc}}$, it considers the number of units of that asset which were started up, $v_{a,k_y,b_{k_y}}^{\text{start up}}$, or shut down, $v_{a,k_y,b_{k_y}}^{\text{shut down}}$, in each time block $b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}}$ or $b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{sd}}$, of every representative period $k_y \in \mathcal{K}_y$, of every year $y \in \mathcal{Y}$ being modelled. Each such start-up and shut-down event adds a cost of $p_{a,y}^{\text{start up costs}}$ and $p_{a,y}^{\text{shut down costs}}$ to the objective function, respectively. The same formulation for start-up and shut-down costs is commonly used in literature, both in clustered unit commitment [12] and single unit [13, 14] formulations.

2.3 Full Start-Up and Shut-Down Constraints

In order to ensure that the start-up and shut-down variables introduced in (1) correctly model the behaviour of generators, certain logical constraints are needed. The first set of such constraints added to Tulipa is shown below.

$$v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}) - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}-1) = v_{a,k_y,b_{k_y}}^{\text{start up}} - v_{a,k_y,b_{k_y}}^{\text{shut down}} \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}} \quad (2a)$$

$$v_{a,k_y,b_{k_y}}^{\text{start up}} \leq v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}) \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}} \quad (2b)$$

$$v_{a,k_y,b_{k_y}}^{\text{shut down}} \leq v_{a,y}^{\text{available units}} - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}) \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{sd}} \quad (2c)$$

$$v_{a,k_y,b_{k_y}}^{\text{start up}}, v_{a,k_y,b_{k_y}}^{\text{shut down}} \in \mathbb{Z}_{\geq 0} \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}} \quad (2d)$$

Equation (2a) defines the start-up and shut-down variables in terms of the difference in the number of units which are operating in two consecutive time blocks, b_{k_y} and $b_{k_y} - 1$. Here, $B_{a,y,k_y}^{\text{uc}}(b_{k_y})$ is a function which maps the time block in which $v_{a,k_y,b_{k_y}}^{\text{start up}}$ and $v_{a,k_y,b_{k_y}}^{\text{shut down}}$ are defined, to the corresponding time block in the temporal resolution of $v_{a,k_y}^{\text{units on}}$, which has the same start time as b_{k_y} .

Equations (2b) and (2c) state the upper bounds of the start-up and shut-down variables, respectively. Equation (2b) models the fact that if $v_{a,k_y,b_{k_y}}^{\text{start up}}$ units of a certain asset are started up in time block b_{k_y} , then at least as many units of that asset must be operating in the same time block. Similarly, (2c) states that the greatest number of units which can be shut-down in a given time block cannot be greater than the number of units which are not operating in the same time block, which is equal to the difference between the number of available units, $v_{a,y}^{\text{available units}}$ and units which are on. Finally, (2d) specifies the domain of the start-up and shut-down variables.

The set of constraints defined in (2a)-(2d) is based on a tight formulation of minimum up and down times [15] which are commonly used in UC models, for example in [14, 16]. They have been adapted from a binary to a clustered unit commitment formulation in [17], and researchers from TNO have further modified them to make them compatible with Tulipa's fully flexible temporal resolutions.

2.4 Compact Start-Up and Shut-Down Constraints

Alongside the full start-up and shut-down constraints described in (2a)-(2d), a compact set of constraints is considered. They replace the expressions in (2a-2c) with lower bounds, meaning that they increase the size of the search space. However, given that the compact constraints are still tight in the direction of the objective function, and they have one fewer equation than the full constraints, they are expected to decrease the computational time of the model compared to the full constraint set [18]. The compact set of constraints is shown in the equations below.

$$v_{a,k_y,b_{k_y}}^{\text{start up}} \geq v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}) - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}-1) \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}} \quad (3a)$$

$$v_{a,k_y,b_{k_y}}^{\text{shut down}} \geq v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}-1) - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}}(b_{k_y}) \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{sd}} \quad (3b)$$

$$v_{a,k_y,b_{k_y}}^{\text{start up}}, v_{a,k_y,b_{k_y}}^{\text{shut down}} \in \mathbb{Z}_{\geq 0} \quad \forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{su}} \quad (3c)$$

Equations (3a) and (3b) place lower bounds on the number of units which can be started up or shut down in a certain time block b_{k_y} , in terms of the difference in the number of units which are on in time blocks b_{k_y} and $b_{k_y} - 1$. Finally, (3c) specifies the domain of the start-up and shut-down variables.

3 Experimental Setup and Results

Section 3.1 describes the case study which was developed, as well as the data sources which were consulted as part of this research project. It is followed by a description of the economic cases and temporal resolutions used in the experiments, in Section 3.2. The section also gives the technical details of the experimental setup, such as the device the cases were ran on, and the procedure used to ensure reliability of the results. Finally, Section 3.3 contains visualisations of the most important results of the study.

3.1 Case Study Description

All simulations presented in this paper are based on the case study which was used in [8] to introduce fully flexible temporal resolutions. It represents a greenfield model of the European Union's energy system, extended with those of Norway, Switzerland, and the UK. As such, it considers only one year of investments and operation, without any generators initially installed.

The original case study consists of renewable energy sources, as well as storage technologies and nuclear power plants. It was expanded with three types of thermal power plants due to their relevance in studying the effect of start-up and shut-down costs on GEP models, as they can be cycled to provide operational reserves. The final list of assets modelled in this paper consists of: offshore and onshore wind farms, solar farms, coal and nuclear power plants, open and closed cycle gas turbines (OCGTs and CCGTs), and battery storage and charge and discharge capacity.

To investigate the effect of start-up and shut-down costs on the optimal solution found by the model, two economic cases are considered. In the *expensive* case, the start-up and shut-down costs of thermal generators are taken from the higher end of the costs found in literature, while in the *cheap* case, the lower costs are used. The costs for coal power plants, OCGTs and CCGTs are taken from [19], while those of nuclear generators are obtained from [20]. The cost data used in the *expensive* and *cheap* cases is shown in Table 1.

Table 1: Start-up and shut-down costs in the *expensive* and *cheap* cases, in euros

Case	Asset	SU Cost (EUR)	SD Cost (EUR)
<i>expensive</i>	Coal	109000	20000
	OCGT	3000	1500
	CCGT	60000	13000
	Nuclear	16500	0
<i>cheap</i>	Coal	48000	12000
	OCGT	2500	1200
	CCGT	42000	10000
	Nuclear	16500	0

To ensure that the case study is realistic, various sources of data were consulted. Firstly, the peak energy demands for each country were taken from [8]. The data on investment costs and minimum operating points of the assets was taken from the PyPSA dataset, and can be found in [21] and [22] respectively. Realistic capacities of generators were estimated using data from [23], and fuel prices for OCGTs and CCGTs, as well as coal and nuclear power plants can be found in [24], [25], and [26] respectively. Finally, the time series of the availability profiles of renewables, as well as the demand profiles per country, were provided by TNO through personal communication [27]. An important point to note is that, unlike in [8], the case study presented in this section does not model trade between countries, due to computational limitations. For a discussion of the effects of including trade in the model, refer to Appendix A. The full input data files can be found at [28].

3.2 Experimental Setup

The aim of this study is to investigate the effect of adding start-up and shut-down costs to a GEP model using a fully flexible temporal resolution. Therefore, the *cheap* and *expensive* economic cases will be ran on multiple temporal resolutions, once with the full start-up and shut-down constraints in (2a)-(2d), and once with the compact constraints in (3a)-(3c). The results of each run will then be compared against a model without start-up and shut-down costs in terms of run time, objective function value, and investment plan.

Six different temporal resolutions will be considered, namely uniform resolutions of 1, 2, 3, 4 and 5 hours, and the fully flexible geographically decreasing resolution introduced in [8]. The aim of the geographically decreasing resolution is to accurately model the Dutch energy system, while considering all other countries in the system with less detail in order to reduce the computation time of the model. The assets of countries will be modelled at lower temporal resolutions the farther away they are from the Netherlands, as shown in Figure 1 (adapted from [8]). As can be seen in the figure, the range of temporal resolutions modelled in the geographically decreasing case is 1-5 hours, which is precisely the reason

for comparing this fully flexible case against uniform resolutions of 1, 2, 3, 4 and 5 hours. Finally, since the geographically decreasing case focuses on the Dutch energy system, the objective function and investment plan of the Netherlands will be considered separately to those of the European system as a whole.

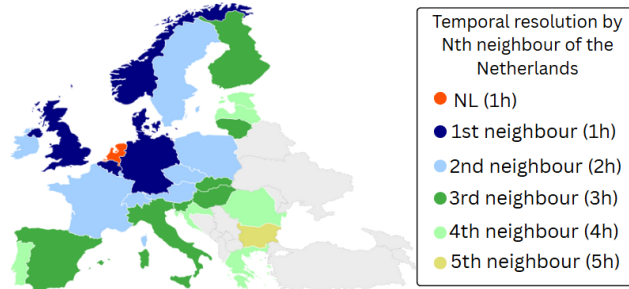


Figure 1: Temporal resolutions per country in the geographically decreasing resolution case. The colour indicates the distance to the Netherlands and the corresponding temporal resolution of the assets in a country.

To supplement the experiments described above, two additional cases will be added. Firstly, to better explore the effect of start-up and shut-down costs on the runtime of the model with the geographical resolution, the extended European model will be considered. It adds ten new countries to the system, and four more generators to each country. The aim of this case is to see how well the fully flexible resolution scales with model size. Secondly, a *medium* economic case will be included to provide a more fine-grained analysis of the sensitivity of the fully flexible temporal resolution to changes in start-up and shut-down costs. The costs of this case are calculated as the means of the cheap and expensive cases.

In order to ensure the validity of the results, each run will be repeated 30 times, with a different seed given to the MILP solver, such that the randomness in runtime introduced by hardware and the solver’s random choices are minimised. As for the objective function values, 10 samples will be used, due to computational limitations. Furthermore, when comparing the objective function values of the runs, it is important to note that the experiments will be ran on a solver with a MIP gap of 0.01%, meaning that if the difference between two objective function values is less than this number, they will be considered to be equal.

The technical specifications of the experiments are as follows. They will be ran on a virtual machine with 16 AMD EPYC 9R14 cores with a maximum clock frequency of 3.7GHz and 32GB of RAM, using Tulipa energy model version 0.15.0 [9]. They have been written in the Julia programming language version 1.11.5 [29], and make use of the BenchmarkTools package [30]. Finally, the MILP solver used is Gurobi 12 [31].

3.3 Numerical Results

This section contains visualisations of the most important experiment results. The raw data, as well as the code used to produce the visualisations, can be found at [28].

Firstly, Figure 2 shows the average runtimes of the model for each temporal resolution, when ran without any start-up or shut-down constraints, and with the full and compact constraint sets. The runtimes for both the cheap and expensive cases are shown in Figures 2a and 2b respectively. Finally, Figure 3 shows the runtime of the extended European model

with the geographically decreasing temporal resolution, for all constraint sets and the cheap and expensive economic cases.

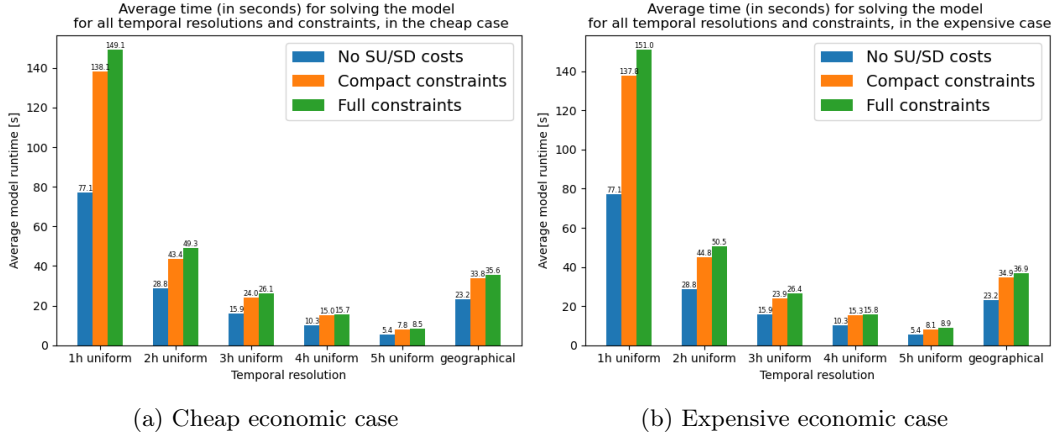


Figure 2: Average runtime of the model in seconds, for different temporal resolutions and constraints.

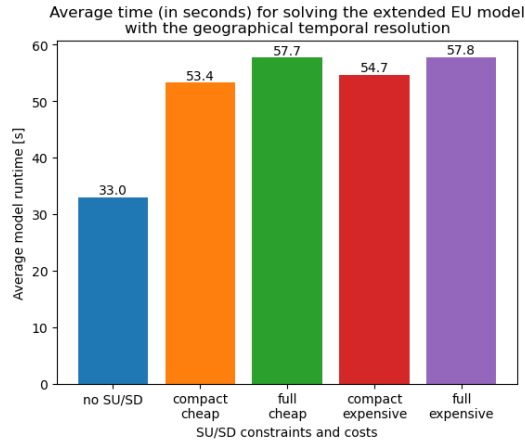


Figure 3: Average runtime (in seconds) of the extended European model with the geographically decreasing temporal resolution.

Figures 4 and 5 show the tradeoff between model solving time and accuracy in the objective function in the expensive economic case, focusing on the costs for the entire energy system and the Netherlands respectively. The x-axis represents the average time taken to solve the model. The y-axis is the absolute value of the percentage error for each case, when compared to the objective function value of the 1-hour resolution with the full constraint set. This case was chosen as the reference point because it has the highest temporal resolution and it models start-up and shut-down costs, making it the most accurate. Note that the 1-hour resolution with compact constraints is equally as accurate, and the model with the full constraint set was chosen over it arbitrarily. Both figures also highlight the Pareto front,

with Figure 5 additionally showing both the Pareto front of all the points, as well as with the geographical temporal resolutions removed. Finally, the corresponding plots for the cheap economic case are omitted, as they are identical to Figures 4 and 5.

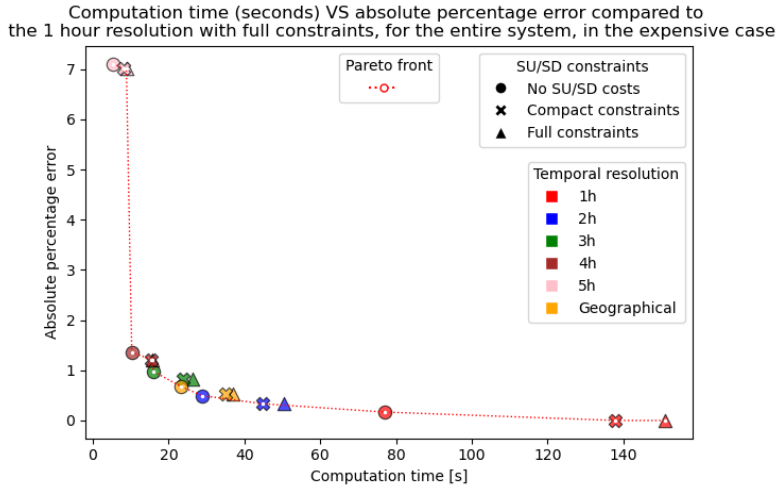


Figure 4: Average runtime of the model in seconds, plotted against percentage absolute error compared to the 1-hour resolution with the full constraint set, for the expensive case.

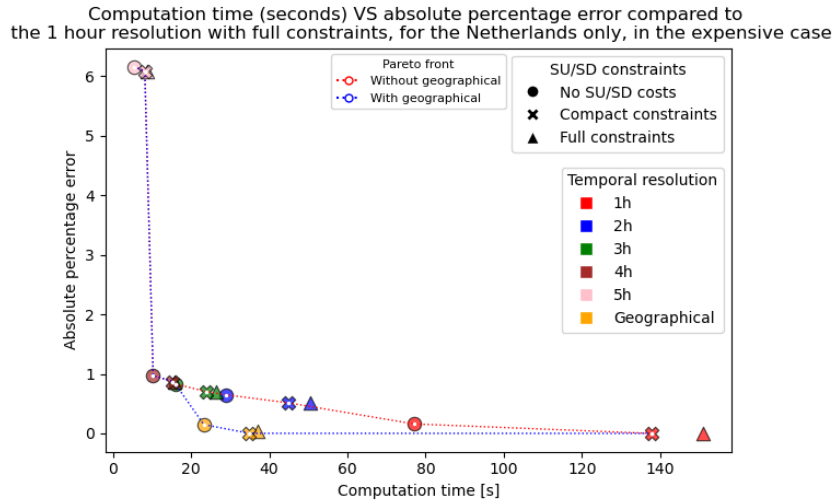


Figure 5: Average runtime of the model in seconds, plotted against percentage absolute error in the objective function for the Netherlands compared to the 1-hour resolution with the full constraint set, for the expensive case

Figure 6 shows how the impact of adding start-up and shut-down costs differs per temporal resolution and economic case. This impact for a specific case is measured by the percentage difference between the objective function value of that case and the same case

without start-up and shut-down costs. Figure 6b shows the changes in the objective function value for the total energy system, for every combination of full and compact constraint sets with the cheap and expensive economic cases. Note that the values for the full constraint set are not visible in the plot, as they are almost exactly equal to those of the compact constraints. Similarly, Figure 6a contains the percentage differences in the objective function, but only for the Netherlands. It additionally includes data points for the cost difference in the overall system, with the geographical resolution with the full constraint set, in both economic cases. These are included for ease of comparison between the two plots.

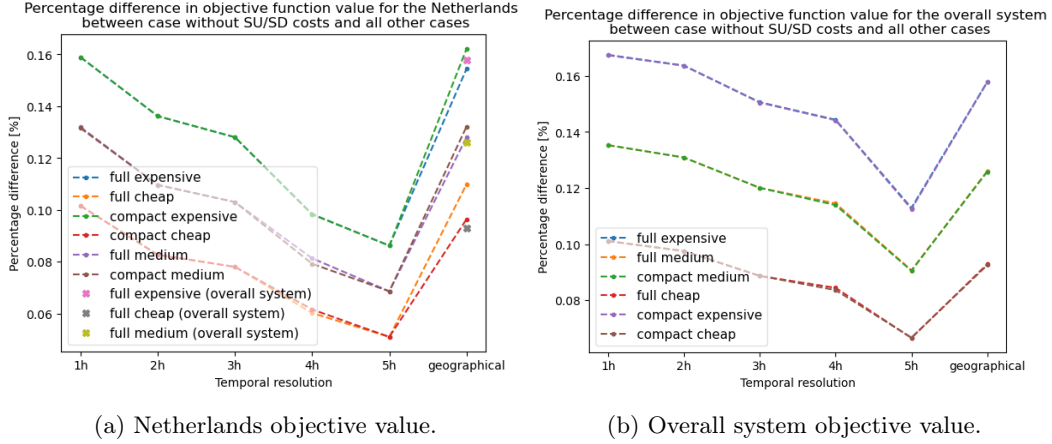


Figure 6: Average percentage difference in the objective function value caused by adding SU/SD costs to each temporal resolution.

To compare the different optimal solutions found by the model, Figure 7 shows the standard deviations in the objective function value for the overall energy system (7a) and for the Netherlands (7a).

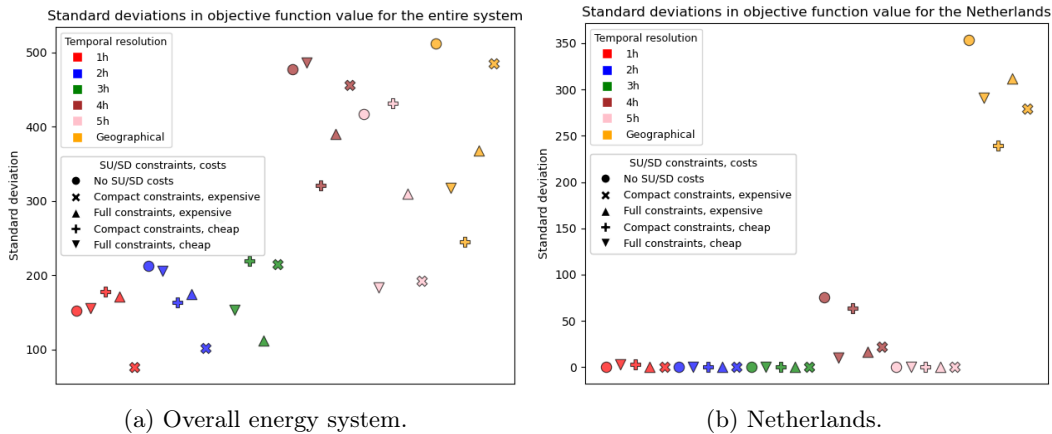


Figure 7: Standard deviation of the objective function value.

Finally, Figure 8 shows the changes in the investment plan for the Dutch energy system

caused by including start-up and shut-down costs. For each asset and SU/SD cost and constraint case, the percentage difference in invested capacity is calculated, when compared to the case without start-up and shut-down costs. Figure 8a highlights the changes when using an hourly resolution, while Figure 8b shows the geographical resolution.

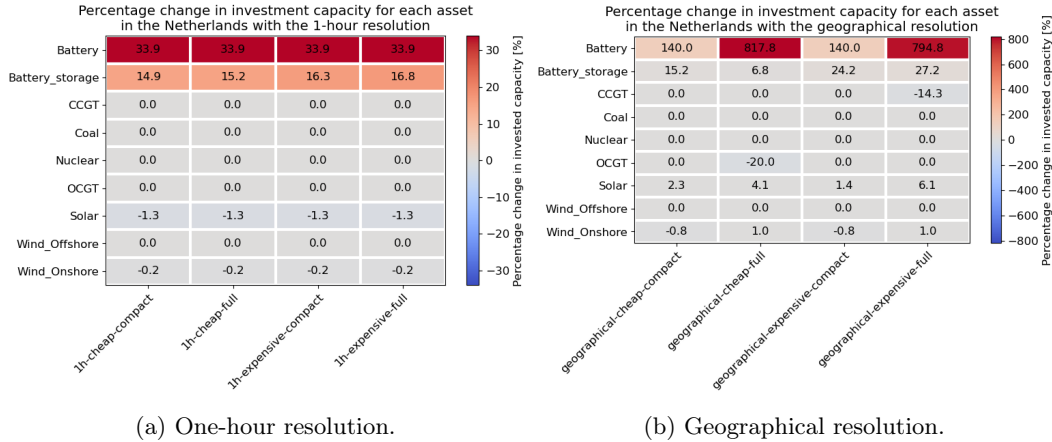


Figure 8: Percentage changes in investment plan in the Netherlands for the 1-hour and geographical resolutions, compared to the case without start-up and shut-down costs.

4 Discussion

This section discusses the results of the study. Section 4.1 analyses the effect of start-up and shut-down constraints on the runtime of the model. Then, Section 4.2 discusses the change in accuracy when the constraints are added, and the tradeoff between accuracy and runtime of the model. The changes in investment plan are analysed in Section 4.3. The section concludes with a reflection on the ethical implications of the study in 4.4.

4.1 Effects of Start-Up and Shut-Down Constraints on Model Solving Time

As can be seen in Figure 2, the addition of start-up and shut-down constraints increases the time taken to solve the model for every temporal resolution. Furthermore, by comparing Figures 2a and 2b, it can be seen that the values of the start-up and shut-down costs do not impact the time taken to solve the model, as the graphs for the expensive and cheap economic cases are nearly identical.

Additionally, the figures reveal that the model is solved faster when using the compact constraint set compared to the full constraints, regardless of the temporal resolution. This is to be expected, as the compact constraint set results in the model having fewer start-up and shut-down variables and constraints overall. However, this difference is less visible for the temporal resolutions with shorter runtimes, such as the 4 and 5-hour uniform resolutions, and the geographically decreasing resolution. This is also in line with expectations, as models with low temporal resolutions already have their number of variables and constraints greatly reduced compared to those with higher resolutions.

If the geographically decreasing temporal resolution is used on a model with more countries and generators, the difference in runtime for the full and compact constraint sets becomes more pronounced. As can be seen in Figure 3, the difference in runtime of the extended EU model for the compact and full constraints in the cheap case is 8.0%, which is greater than the corresponding quantity of 5.3% for the smaller geographically decreasing case study.

4.2 Effects of Start-Up and Shut-Down Costs on the Objective Function Value

Figures 4 and 5 show the tradeoff between model runtime and accuracy. From the first figure, it can be seen that, when considering the accuracy over the entire energy system, adding start-up and shut-down costs causes the geographical temporal resolution to move away from the Pareto front, indicating a worse performance. This happens because the 2-hour temporal resolution preserves the overall temporal detail of the availability and demand profiles of the countries better than the geographical resolution, which has a greater impact on the overall accuracy than adding start-up and shut-down costs.

On the other hand, when considering the accuracy for the Dutch energy system only, including the compact set of start-up and shut-down constraints exceeds the Pareto front, meaning that it improves the model’s performance. This can be explained by considering the results of [8], which showed that the geographically decreasing resolution, without start-up and shut-down costs, exceeds the Pareto front when focusing on the Dutch energy system. Due to this decrease in error (from 0.61% to 0.15%) for the case without start-up and shut-down costs, the geographical resolution now performs better than the 2-hour resolution, meaning that the additional computational time of the compact start-up and shut-down constraints is justified by their contribution to the accuracy of the solution. Finally, it can be seen that even when only considering the Dutch energy system, the case with the full set of start-up and shut-down constraints does not lie on the Pareto front. This is because the full constraints do not provide any additional accuracy, while increasing the computation time of the model.

While the geographical temporal resolution maintains a high level of accuracy when it comes to the objective function value in the Netherlands, it also introduces the most variance compared to the other temporal resolutions, which can be seen in Figure 7. Furthermore, Figure 6 shows that the different sets of constraints are sensitive to the values of the start-up and shut-down costs, when considering the objective function for the Netherlands. Specifically, in the expensive economic case, the model with the compact constraint set yields a greater increase in objective function value than the model with the full constraint set. The same behaviour can be seen in the medium economic case, but to a lesser extent. Conversely, this pattern is reversed for the cheap economic case, in which the full constraint set results in higher costs for the Netherlands. Finally, Figure 6b shows that the overall objective function value does not depend on the set of constraints which was used, as all of the values must be within 0.01% of the optimal solution, allowing for no significant variance.

4.3 Effects of Start-Up and Shut-Down Costs on the Investment Plan

Figures 8a and 8b show how the investment plan for the Netherlands changes for the 1-hour and geographically decreasing temporal resolutions when start-up and shut-down costs are

added.

In the case of the 1-hour resolution, adding start-up and shut-down costs leads to more batteries being purchased. This is consistent with the findings of [2], which identified storage technologies as an important source of flexibility. Furthermore, the investment plan seems to not be greatly affected by the changes in start-up and shut-down costs between the cheap and expensive economic cases. The only asset which sees a change in invested capacity between these cases is battery storage, with an average value of 1.5%.

Similarly to the 1-hour resolution, adding start-up and shut-down costs to the geographical resolution results in an increase in purchased storage capacity, and a large spike in charge and discharge capacity. However, this resolution seems to be sensitive to the constraint set used. Namely, using the full constraint set causes the model to purchase fewer thermal generators, while significantly increasing investments into batteries compared to the compact constraint set. Furthermore, the investment plan changes more significantly than that of the 1-hour resolution between the different economic cases. In the cheap case with the full constraints, the investment capacity of OCGTs falls by 20%, while all other thermal generators remain unchanged. In the expensive case, however, 14.3% fewer CCGTs are bought. This is believed to be due to the fact that the start-up and shut-down costs of CCGTs decrease by a higher percentage (30%) compared to OCGTs (16.7%) between the expensive and cheap cases.

4.4 Responsible Research

This section provides a reflection on the ethical implications of this study. The relevant challenges which were identified and addressed throughout the project are those of data collection, reproducibility of the study, and impacts of this research on society.

Firstly, accurately modelling the European energy system is of great importance to ensuring the validity of the study. To this aim, we have taken great care to verify that all of our data comes from reputable and well-documented sources, such as the International Energy Agency [25], the Global Power Plant Database [23], the open-source PyPSA project [20], and TNO’s Tulipa energy model. Furthermore, since the aim of the study was to investigate the impact of start-up and shut-down costs on models with fully flexible temporal resolutions, obtaining realistic parameters for the SU/SD costs of thermal generators was paramount to the accuracy of the study. Therefore, they were sourced from existing literature on unit commitment models, namely [19], and were compared against other datasets, such as that of the PyPSA project [22]. Finally, regarding the ethical implication of the ways in which the data was collected, we note that all of the referenced datasets are publicly available, and do not include any personal or sensitive information.

Additionally, the study was designed with reproducibility in mind from the start. To implement the start-up and shut-down constraints, the open-source Tulipa energy model was used [9], and our additions to it have been made available at [32]. Furthermore, the full input data files and the code used to generate them, the script for running the experiments, the raw data produced by running them, as well as the code used to process and plot the data is available at [28]. Therefore, every step of the study is easily reproducible. The only exception is the fact that the Gurobi optimiser, a proprietary program, was used to solve the models. As such, it might not be freely accessible to everyone, despite the fact that Gurobi offers free academic licenses. To overcome this issue, the open-source HiGHS solver can be used instead [33].

Lastly, we believe that the societal impact of the project is positive. Given that it aims to

improve the accuracy of energy system optimisation models, it could lead to better informed policies if it were used by governments or network operators. However, in case the start-up and shut-down constraints contain implementation errors, the model could produce incorrect results, leading to poorly informed decisions. To mitigate this issue, the implementation of the constraints was verified, both manually and automatically, on multiple different case studies. It has also been made open-source, such that it can be easily verified by anyone in the scientific community. Finally, since the impact of start-up and shut-down constraints was evaluated using a model based on the European energy system, the results might not generalise to the energy systems of other regions. A step taken to minimise this issue was using a wide range of generator start-up and shut-down costs, and not necessarily focusing on only those commonly found in the EU. Furthermore, using the data generation scripts at [28], the effects of start-up and shut-down costs on different energy systems can easily be investigated.

Therefore, given the facts that the data used for the study was obtained from reputable sources and does not contain any sensitive information, and that every part of the study is publicly available and thus reproducible, and that the project has a positive impact on society, we conclude that the research has been conducted responsibly and that it meets the ethical standards of TU Delft.

5 Conclusions and Future Work

The inclusion of unit commitment constraints in generation expansion planning (GEP) models has been a well-studied topic in recent literature. Research has shown that including operational constraints, such as start-up and shut-down costs of generators, can improve the accuracy of GEP models, especially those modelling systems with a high penetration of renewable energy sources. However, including these operational details also increases the computational cost of the models, making them difficult to solve if they are modelling longer planning horizons. A common way of decreasing the computation time of GEP models is by lowering their temporal resolution, which comes with the trade-off of lowering the model's accuracy.

The concept of fully flexible temporal resolutions has been recently introduced to GEP models to address this issue. An example of such a resolution is the geographically decreasing resolution, which allows for a target country to be modelled at a high resolution, while other countries have their resolution decreased in proportion to their distance to the target country. It has been shown that this approach can reduce the computation time of a GEP model, while maintaining a high accuracy in the target country. However, fully flexible temporal resolutions have only been investigated using GEP models without unit commitment constraints, so the effect of adding start-up and shut-down costs to models with such temporal resolutions is unknown.

The aim of this study was to investigate the effects of start-up and shut-down costs on the computation time, objective function value, and investment plan of a GEP model with a fully flexible temporal resolution. The first important conclusion of the study is that, if start-up and shut-down costs are to be included in a model with a fully flexible temporal resolution, a compact set of constraints should be used to do so instead of a full set of constraints which is tight in all directions. This is justified by the fact that the compact constraint set resulted in a smaller increase in computation time compared to the full constraint set, and that the percentage difference in computation time between the two constraint sets increased with the size of the model.

The second finding is that adding start-up and shut-down constraints has a positive impact on the model with a geographically decreasing temporal resolution, when considering the tradeoff between the runtime of the model and the accuracy for the target country. Namely, when compared to uniform resolutions of 1-5 hours, both with and without start-up and shut-down costs, the geographically decreasing resolution with SU/SD costs exceeds the Pareto front. Importantly, this result is achieved when using the compact constraint set, but not with the full constraints. This is because the latter offer no additional accuracy, while increasing computation time. On the other hand, it was also observed that the addition of start-up and shut-down costs has different impacts on the objective function value for the target country depending on the values of the costs themselves. Namely, the compact constraints lead to a higher increase in the objective function if more expensive start-ups and shut-downs are considered, and vice versa. Since the differences between the two sets of constraints were found to be relatively low, we still advocate for the use of the compact set of constraints, due to their lower runtime. However, caution is still advised when using the geographically decreasing temporal resolution, as it was shown to produce the highest variance in solutions for the target country compared to uniform resolutions of 1-5 hours.

Finally, the study has shown that adding start-up and shut-down costs to a model has different effects on the investment plan, depending on the temporal resolution used. Compared to the hourly resolution, adding SU/SD costs to the geographically decreasing resolution greatly increases the amount of battery charge and discharge capacity purchased. This difference is even more explicit when using the full constraint set, as it causes the model to buy significantly fewer thermal generators, and replace them with additional charge and discharge capacity.

Based on the results of this study, the following future research is proposed. Firstly, it was observed that the model never invests into nuclear generators, most likely due to their large investment cost. To model a more realistic scenario, we propose a multi-year investment model with a time-span longer than the technical lifetime of all the generators in the case study. This way, technical lifetimes of both renewable and thermal generators will need to be considered, which could affect the investment mix, as nuclear generators usually have the longest technical lifetime. This would, in turn, have an effect on the optimal operation schedule of the generators, and thus on the incurred start-up and shut-down costs.

Secondly, this study has assumed that start-up and shut-down costs of generators are constant. However, a more realistic approach would involve modelling these costs as exponentially increasing the longer a generator remains offline [34], which is known as hot and cold starts. This would lead to more complex operational dynamics, and could have large impacts on the optimal operation schedule. This is especially relevant for the geographically decreasing temporal resolution, as the countries modelled with lower resolutions would be forced to keep their thermal generators turned off for longer periods of time, thus increasing their start-up costs.

Acknowledgments

I would like to thank Maaike Elgersma and Dr.ir. German Morales-España for their feedback and guidance throughout the project, as well as Diego Alejandro Tejada Arango and Ni Wang for their support and help with the Tulipa energy model.

Appendix A

This section presents the results of the European energy system case study with added trade between countries. The data about the connections of different countries' energy systems was taken from [8], and each experiment was ran with 15 samples. The MIP gap was increased from 0.01% to 0.1% due to the long runtime of the case study. Only the expensive economic case is considered. Finally, to further investigate the effects of start-up and shut-down costs on different configurations of fully flexible temporal resolutions, the temporal resolution of the geographically decreasing case was changed to the one shown in Figure 9.

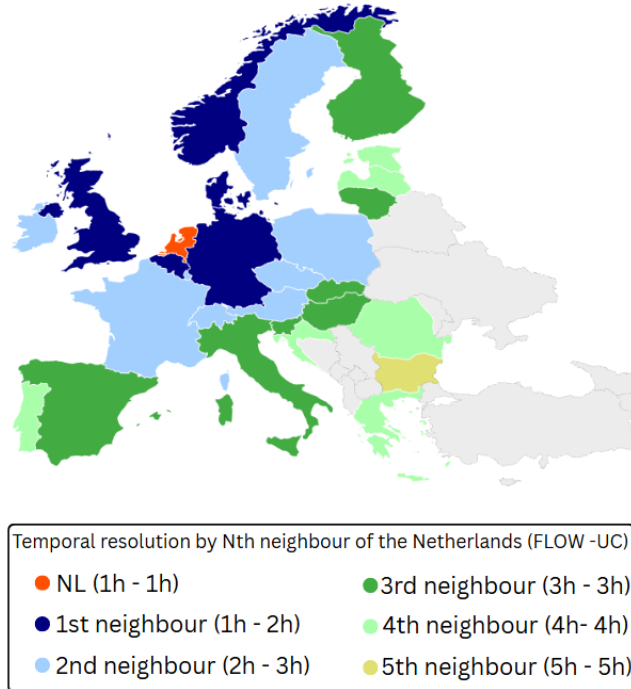


Figure 9: Temporal resolutions per country in the geographically decreasing resolution case with trade. The colour indicates the level of connection to the Dutch energy system and the corresponding temporal resolution of the flows and assets in a country.

Figure 10 shows the average runtimes of the model for each temporal resolution, both with the full and compact constraint sets, as well as without any start-up and shut-down costs. Similarly to the case without trade, it can be seen that adding start-up and shut-down costs increases the runtime of the model, with the full constraint set making the model significantly slower. However, with the inclusion of trade, the geographically decreasing temporal resolution has the worst runtime, approximately double that of the hourly resolution. This likely happens because of the increased number of constraints in which the flow and SU/SD variables have temporal resolutions which are not multiples of each other. Additionally, we believe that this configuration of temporal resolutions increases runtime due to integer variables being used. To investigate this hypothesis, the case study was re-ran as a linear model without integer variables. The new runtimes are shown in Figure 11. It can be seen that

in this case, the geographically decreasing resolution has a lower runtime than the hourly resolution, which is consistent with the results of [8].

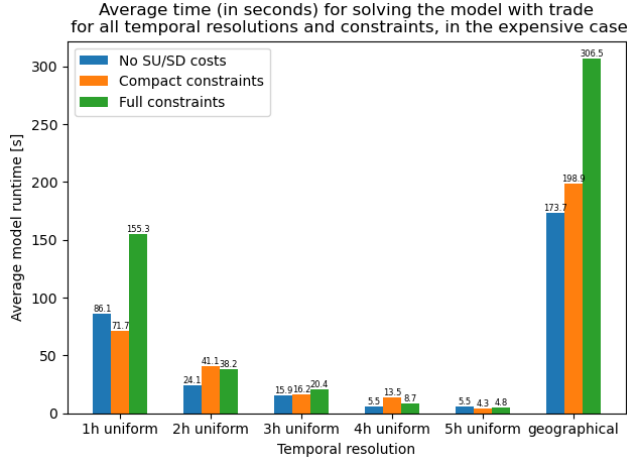


Figure 10: Average runtime (in seconds) of the model with trade between countries.

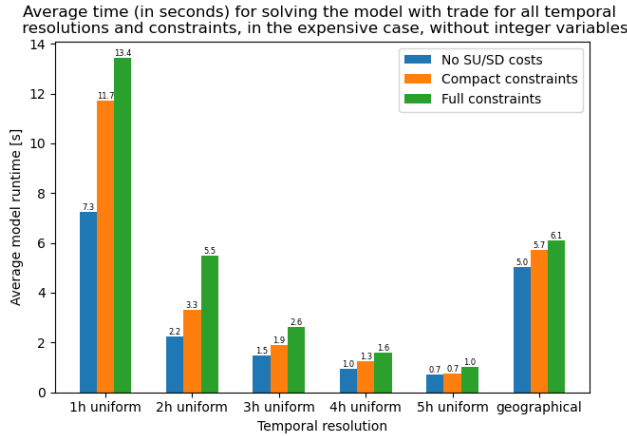


Figure 11: Average runtime (in seconds) of the model with trade between countries, without integer variables.

Figures 12 and 13 show the change in investment plan for the overall energy system when start-up and shut-down costs are added to the hourly and geographically decreasing temporal resolution, respectively. The changes in investment plan for the hourly resolution are similar to those for the case study without trade between countries. More batteries and charge and discharge capacity are purchased, with small changes to the other assets. One major difference is the fact that slightly fewer CCGTs are purchased, likely due to additional flexibility being provided by the ability to trade energy between countries. On the other hand, for the geographically decreasing temporal resolution, significantly less storage and charge and discharge capacity is purchased, as well as fewer CCGTs, while slightly more

offshore wind farms are invested into. It is believed that this is the result of countries with lower temporal resolutions, such as Bulgaria, investing into more renewable energy sources and providing additional flexibility to other countries through trade. This happens because lower temporal resolutions cause the availability profiles of renewable energy sources to be averaged over multiple hours, resulting in smoother transitions between them. This reduces the variations in the power output of renewable energy sources, thus reducing the need for flexibility which is usually provided by batteries and thermal generators.

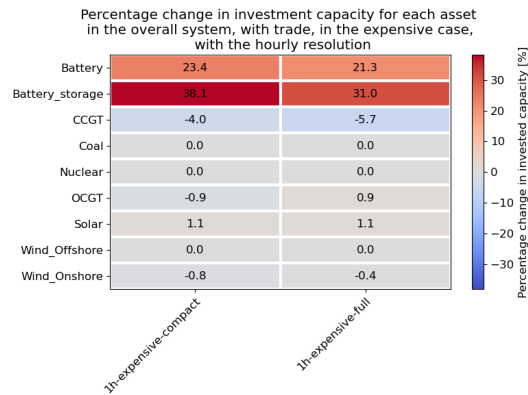


Figure 12: Percentage change in investment plan in the overall energy system with trade for the hourly resolution.

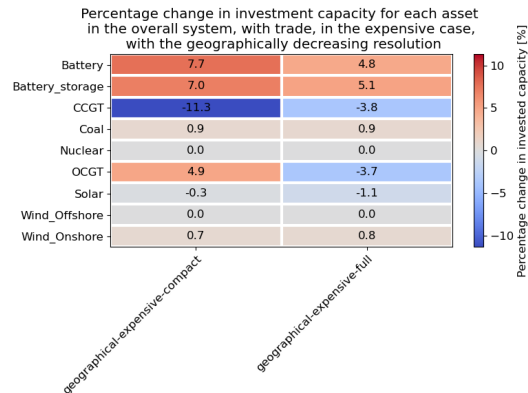


Figure 13: Percentage change in investment plan in the overall energy system with trade for the geographically decreasing resolution.

References

- [1] Nikolaos E. Koltsaklis and Athanasios S. Dagoumas. “State-of-the-art generation expansion planning: A review”. en. In: *Applied Energy* 230 (Nov. 2018), pp. 563–589. ISSN: 03062619. DOI: 10.1016/j.apenergy.2018.08.087. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261918312583> (visited on 04/25/2025).
- [2] 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. URL: <https://linkinghub.elsevier.com/retrieve/pii/S0306261919315302> (visited on 04/23/2025).
- [3] Mark O’Malley, Aonghus Shortt, and Juha Kiviluoma. “Accommodating Variability in Generation Planning”. en. In: (Feb. 2023). DOI: 10.1109/TPWRS.2012.2202925.
- [4] B. Palmintier and M. Webster. “Impact of unit commitment constraints on generation expansion planning with renewables”. en. In: *2011 IEEE Power and Energy Society General Meeting*. Journal Abbreviation: 2011 IEEE Power and Energy Society General Meeting. July 2011, pp. 1–7. ISBN: 1944-9925. DOI: 10.1109/PES.2011.6038963.
- [5] Hugo Chandler. “Empowering variable renewables-options for flexible electricity systems”. In: (2008).
- [6] 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. URL: <https://www.mdpi.com/1996-1073/15/4/1296> (visited on 04/23/2025).
- [7] J. Haas et al. “Challenges and trends of energy storage expansion planning for flexibility provision in low-carbon power systems – a review”. en. In: *Renewable and Sustainable Energy Reviews* 80 (Dec. 2017), pp. 603–619. ISSN: 13640321. DOI: 10.1016/j.rser.2017.05.201. URL: <https://linkinghub.elsevier.com/retrieve/pii/S1364032117308377> (visited on 05/02/2025).
- [8] Zhi Gao et al. *Fully Flexible Temporal Resolution for Energy System Optimization*. en. Nov. 2025. DOI: 10.2139/ssrn.5214263.
- [9] *Tulipa*. en. URL: <https://github.com/TulipaEnergy> (visited on 04/27/2025).
- [10] Diego A. Tejada-Arango et al. *Tulipa Energy Model: Mathematical Formulation*. en. arXiv:2309.07711 [math]. Sept. 2023. DOI: 10.48550/arXiv.2309.07711. URL: <http://arxiv.org/abs/2309.07711> (visited on 04/30/2025).
- [11] Abel Soares Siqueira et al. *Tulipa Energy Model*. Apr. 2025. DOI: 10.5281/ZENODO.8363262. URL: <https://zenodo.org/doi/10.5281/zenodo.8363262> (visited on 04/23/2025).
- [12] Xuhan Zhang et al. “An efficient generator maintenance scheduling model based on unit clustering and linear relaxation”. In: *Electric Power Systems Research* 230 (May 2024), p. 110300. ISSN: 0378-7796. DOI: 10.1016/j.epsr.2024.110300. URL: <https://www.sciencedirect.com/science/article/pii/S0378779624001883> (visited on 05/20/2025).

- [13] L. L. Garver. “Power Generation Scheduling by Integer Programming-Development of Theory”. In: *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems* 81.3 (1962), pp. 730–734. DOI: 10.1109/AIEEPAS.1962.4501405.
- [14] Germán Morales-España, Jesus M. Latorre, and Andres Ramos. “Tight and Compact MILP Formulation for the Thermal Unit Commitment Problem”. In: *IEEE Transactions on Power Systems* 28.4 (2013), pp. 4897–4908. DOI: 10.1109/TPWRS.2013.2251373.
- [15] Deepak Rajan and Samer Takriti. *Minimum Up/Down Polytopes of the Unit Commitment Problem with Start-Up Costs*. en. Tech. rep. RC23628. June 2005.
- [16] Maurice Queyranne and Laurence A. Wolsey. “Tight MIP formulations for bounded up/down times and interval-dependent start-ups”. In: *Mathematical Programming* 164.1-2 (2016), pp. 129–155. DOI: 10.1007/s10107-016-1079-2.
- [17] Jelle Meus, Kris Poncelet, and Erik Delarue. “Applicability of a Clustered Unit Commitment Model in Power System Modeling”. en. In: *IEEE Transactions on Power Systems* 33.2 (Mar. 2018), pp. 2195–2204. ISSN: 0885-8950, 1558-0679. DOI: 10.1109/TPWRS.2017.2736441. URL: <https://ieeexplore.ieee.org/document/8003295/> (visited on 04/24/2025).
- [18] Maaïke Elgersma. Personal communication. Apr. 24, 2025.
- [19] F. Aliprandi, A. Stoppato, and A. Mirandola. “Estimating CO2 emissions reduction from renewable energy use in Italy”. In: *Renewable Energy* 96 (Oct. 2016), pp. 220–232. ISSN: 0960-1481. DOI: 10.1016/j.renene.2016.04.022. URL: <https://www.sciencedirect.com/science/article/pii/S0960148116303160> (visited on 05/31/2025).
- [20] Tom Brown et al. *PyPSA-Eur: An open sector-coupled optimisation model of the European energy system*. original-date: 2017-10-11T23:54:41Z. May 2025. URL: <https://github.com/PyPSA/pypsa-eur> (visited on 05/31/2025).
- [21] *technology-data/inputs/EWG_costs.csv at master · PyPSA/technology-data*. en. URL: https://github.com/PyPSA/technology-data/blob/master/inputs/EWG_costs.csv (visited on 05/31/2025).
- [22] *pypsa-eur/data/unit_commitment.csv at master · PyPSA/pypsa-eur*. en. URL: https://github.com/PyPSA/pypsa-eur/blob/master/data/unit_commitment.csv (visited on 06/10/2025).
- [23] *Global Power Plant Database - Datasets*. en. URL: <https://datasets.wri.org/datasets/global-power-plant-database> (visited on 05/31/2025).
- [24] *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 (visited on 05/29/2025).
- [25] *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 (visited on 05/29/2025).
- [26] *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 (visited on 05/29/2025).

- [27] Diego Tejada-Arango. Personal communication. May 15, 2025.
- [28] Uros Gluscevic. *Input Data and Results*. June 2025. URL: <https://github.com/urosgluscevic/research-project-data>.
- [29] Julia Programming Language. *Julia*. Version 1.11.5. June 2, 2025. URL: <https://julialang.org>.
- [30] BenchmarkTools.jl. *BenchmarkTools*. Version 1.6.0. June 2, 2025. URL: <https://juliaci.github.io/BenchmarkTools.jl/stable/>.
- [31] Gurobi Optimization. *Gurobi*. Version 12.0.2. June 2, 2025. URL: <https://gurobi.com>.
- [32] CSE3000 Team 51. *TulipaEnergyModel Fork*. June 2025. URL: https://github.com/Cerberus22/TulipaEnergyModel.jl/tree/startup_shutdown_constraints_eq_9.
- [33] HiGHS. *HiGHS Solver*. Version 1.11.0. June 10, 2025. URL: <https://highs.dev/>.
- [34] J.M. Arroyo and A.J. Conejo. “Optimal response of a thermal unit to an electricity spot market”. In: *IEEE Transactions on Power Systems* 15.3 (2000), pp. 1098–1104. DOI: 10.1109/59.871739.