Start-up and Shut-down Capabilities in an Energy System Optimization Model with Flexible Temporal Resolution

Effect of Introducing Start-Up and Shut-Down Capability Constraints to the Tulipa Energy Model

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Abstract

This paper extends the Tulipa energy system optimisation model by incorporating start-up and shut-down capability constraints formulated for Tulipa's fully flexible temporal resolution. The impact of adding these constraints for thermal generators is assessed using a greenfield case study with 7 European countries. Results show that including these constraints increases computation time, but they more realistically represent generator behaviour, which also results in a higher objective function value. Cases where the resolution of assets is not a multiple of the resolution of flows result in uniquely long solving times. The investments, as well as the unit operation trends remain similar on a high level. Batteries are utilised to improve the reduced flexibility, and units with the most flexible start-up/shut-down capabilities become used slightly more often, while the opposite holds for those with the least flexible capabilities. Units also tend to be turned on and off less often. This research contributes to understanding the trade-offs between model complexity and runtime in long-term energy planning.

1 Introduction

In recent years, carbon emissions around the globe have experienced unprecedented growth, which highlights the necessity for the energy sector to switch away from relying on non-renewable resources [1]. Generation expansion planning (GEP) models help to accelerate the renewable energy transition by suggesting an optimal long-term investment plan for installing new technology (such as solar panels, wind turbines) into the energy grid [2].

Sometimes GEP models also include the Unit Commitment (UC) problem, the aim of which is to meet the energy demand by finding a schedule for operating generators that will incur minimal expenses [3]. UC is frequently modelled using Mixed Integer Linear Programming (MILP). This is due to the fast computation time of MILP solvers and advances in numerical optimization utilised in finding the solution [3]. Unit Commitment constraints in a MILP model "represent essential characteristics of the power system" [4], e.g., ramping limits or storage capacity.

Including UC constraints when modelling GEP can provide a more accurate representation of energy system's flexibility, which impacts the types of generators included in the outcome of the solver [5]. Unit Commitment is especially relevant when introducing intermittent renewable energy sources (RES), as their power output is not stable, which requires to consider additional flexibility in the system [2].

However, the computation time becomes undesirably long when scaling a GEP/UC model, especially in terms of the length of the period being modelled [5, 6]. Smaller computation costs have often been achieved by approaches such as lowering the temporal resolution of the model uniformly [7] or down-sampling [8]. However, these usually trade the quality of the solution for faster runtime.

Tulipa energy system optimization model from TNO [9, 10] employs a different approach. Tulipa is a MILP model that combines GEP and UC, and reduces computation times by using fully flexible temporal resolution. This is a novel approach that allows to define complex resolutions independently for each constraint and variable [7]. Therefore, the resolution can be reduced exclusively for less relevant time blocks or assets (e.g., generators of a country far away), decreasing computation load but retaining acceptable solution accuracy [7].

There are two more ways Tulipa reduces the solving time, which are sometimes also found in other models. Firstly, it groups similar generators together instead of modelling individual units, known as clustered UC [11, 12]. Secondly, the model is only solved for a number of days or weeks, called "representative periods", instead of the entire year [13], and any other period in the year is represented by a linear combination of those.

Despite its advantages, Tulipa model does not yet include some important UC constraints, e.g., start-up and shut-down (SU/SD) capabilities [14, 15]. These capabilities are relevant for long term planning, for example, when unit maintenance costs become substantial, and there is a need to balance them with the flexibility provided by fast start-up and shut-down of generators [16]. Furthermore, considering the penetration of RES, thermal units are likely to operate in a high-cycling regime [16], so SU/SD capabilities become more prominent. Other examples of UC constraints Tulipa does not implement are start-up/shut-down costs, trajectories, and minimum up/down time.

Since such constraints have been shown to be crucial in models that are not fully flexible [16], it is relevant to consider the potential effect of adding them to Tulipa. Existing literature has not looked at how introducing the constraints would impact the computation time for fully flexible temporal resolutions. Furthermore, it has not been examined how the generation mix produced by the solver differs in terms of types of assets and their schedule when considering the flexible resolutions.

To address the knowledge gap identified above, this paper investigates how the start-up and shut-down capabilities affect the computation time and the optimal solution of Tulipa under differing flexible temporal resolutions. The results are highlighted in a realistic case study that includes 7 countries in Europe. Outcomes of excluding and including SU/SD capabilities are compared using multiple uniform and non-uniform temporal resolutions.

The paper contributes to existing knowledge by formulating the SU/SD capability constraints for a fully flexible temporal resolution. It shows that that including SU/SD capabilities results in a longer runtime, but improves the model accuracy, which also results in a higher objective function value. Cases where asset resolution is not a multiple of flow resolution are shown to run unusually long. The operational schedules after introducing SU/SD capabilities tend to stay similar, but units with the new constraints tend to be turned on and off less. The investments have only small changes: batteries and units with highly flexible SU/SD capabilities are used more, while those with lower capabilities become less utilised.

The rest of the paper is organised as follows. Section 2 introduces the start-up/shut-down variables and constraints added to Tulipa, together with background that is needed to understand them. Section 3 presents the case study, the experimental setup, and the results. Interpretation of these results and ethical considerations are found in section 4. Section 5 provides a summary, mentions research limitations, and suggests future work directions.

2 Mathematical Formulation

This section starts with explaining the concepts and notation (subsections 2.1-2.3) that are necessary to understand the variables and constraints implemented as part of the research (subsections 2.4-2.5). Their correctness is also illustrated (subsection 2.6).

2.1 Flexible temporal resolution

The model considers milestone years $y \in \mathcal{Y}$. For each year, some representative periods (e.g., days or weeks) $k_y \in \mathcal{K}_y$ are chosen. Each k_y consists of smaller time periods $t \in k_y$. They are often hourly, but time blocks of differing sizes can be considered instead. Figure 1 shows an example of a representative period and some possible partitions of it into time blocks (top row). A time block is noted down as an inclusive range of hours.

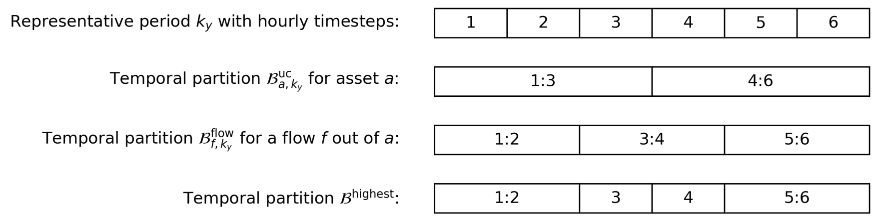


Figure 1: An example of a six hour representative period, 3h uniform temporal partition for an asset, 2h uniform temporal partition for a flow out of it, and the highest resolution.

2.2 Model variables and parameters

Table 1 introduces two important variables that will be used in the SU/SD capability constraints: $v^{\text{units on}}_{a,y,k_y,b_{k_y}}$ and $v^{\text{flow}}_{f,y,k_y,b_{k_y}}$. To combine these two variables with potentially different resolutions, a partition can be constructed for each asset type a to be the combined highest resolution of $\mathcal{B}^{\text{flow}}_{f,y,k_y}$ and $\mathcal{B}^{\text{uc}}_{a,y,k_y}$. An example of constructing a highest resolution is seen in figure 1. For that example, $B^{\text{flow}}_{f,k_y}([1:2]) = [1:2]$, while $B^{\text{uc}}_{a,k_y}([1:2]) = [1:3]$. Appendix A explains in detail how the parameters from table 1 are defined.

Notation	Meaning
$\mathcal{A}^{\text{uc}}_y$	A set of assets that have UC constraints in year y.
$\mathcal{F}$	A set of all flows.
$v^{\text{units on}}_{a,y,k_y,b_{k_y}}$	A **variable** that shows how many units of asset $a \in \mathcal{A}^{\text{uc}}_y$ are turned on in block b_{k_y}.
$v^{\text{flow}}_{f,y,k_y,b_{k_y}}$	A **variable** that shows how much energy units of asset a produce that flows out to asset a' in block b_{k_y} with $f = (a, a')$ and $f \in \mathcal{F}$.
$\mathcal{B}^{\text{uc}}_{a,y,k_y}$	A partition for $v^{\text{units on}}_{a,y,k_y,b_{k_y}}$.
$\mathcal{B}^{\text{flow}}_{f,y,k_y}$	A partition for $v^{\text{flow}}_{f,y,k_y,b_{k_y}}$.
$B^{\text{uc}}_{a,k_y}(b_{k_y})$	A function that finds in which block of $\mathcal{B}^{\text{uc}}_{a,y,k_y}$ the block $b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y}$ is contained.
$B^{\text{flow}}_{f,k_y}(b_{k_y})$	A function that finds in which block of $\mathcal{B}^{\text{flow}}_{f,y,k_y}$ the block $b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y}$ is contained.
$p^{\text{max}}_{a,y,k_y,b_{k_y}}$	Maximum operating point of asset a in block b_{k_y}.
$p^{\text{min}}_{a,y,k_y,b_{k_y}}$	Minimum operating point of asset a in block b_{k_y}.
$p^{\text{ramp up}}_{a,y,k_y,b_{k_y}}$	Maximum ramping up rate of asset a in block b_{k_y}.
$p^{\text{ramp down}}_{a,y,k_y,b_{k_y}}$	Maximum ramping down rate of asset a in block b_{k_y}.

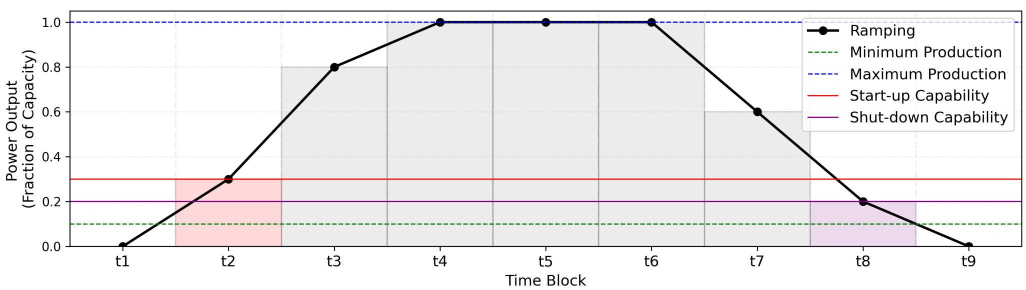
Table 1: Definitions of sets, variables, partitions, functions, and parameters that are later used in SU/SD constraints.

The parameters $p^{\text{ramp up}}_{a,y,k_y,b_{k_y}}$ and $p^{\text{ramp down}}_{a,y,k_y,b_{k_y}}$ are relevant for ramping when a unit is operating at least at p^{min}. As it is discussed in the next subsection, ramping capabilities might not be the same during start-up (operation is at zero) or shut-down (operation goes to zero).

2.3 Start-up and shut-down capabilities

The ramping capabilities of a unit might be different from regular when the unit is starting up. For example, say $p^{\text{min}} = 0.1$ (10% of the unit's capacity), $p^{\text{max}} = 1$, $p^{\text{ramp up}} = 0.5$. In that case, when a unit is on and producing at 0.4, it can produce at most at 0.9, and at least at 0.1 in the next time block. However, when a unit is off, then it might not be able to immediately go from 0 to $0.1 + 0.5 = 0.6$, it might at most be able to produce at 0.3. Something similar might be true when the unit shuts down.

This behaviour is modelled by SU/SD capability constraints. The capabilities are denoted by parameters $p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}}$ and $p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}}$. Figure 2 displays the scenario described above, with $p^{\text{ramp down}} = 0.4$, $p^{\text{shut down ramp}} = 0.2$. The variables from the table below the graph are explained in the next subsection.



	t1	t2	t3	t4	t5	t6	t7	t8	t9
$v^{\text{units on}}$	0	1	1	1	1	1	1	1	0
$v^{\text{start up}}$	0	1	0	0	0	0	0	0	0
$v^{\text{shut down}}$	0	0	0	0	0	0	0	0	1

Figure 2: Illustration of a unit turning on, ramping up and down, and turning off.

2.4 New variables

As part of this research, start-up an shut-down variables were added to Tulipa. Variable $v^{\text{start up}}_{a,y,k_y,b_{k_y}}$ indicates how many units are starting up in block $b_{k_y} \in \mathcal{B}^{\text{uc}}_{a,y,k_y}$, and $v^{\text{shut down}}_{a,y,k_y,b_{k_y}}$ represents the number of units that shut down. They are defined in the temporal resolution of $\mathcal{B}^{\text{highest}}$, but only for the blocks that start at the same time as a block in $\mathcal{B}^{\text{uc}}$. Considering figure 1, their resolution would be $\mathcal{B}^{\text{su}}_{a,y,k_y} = \mathcal{B}^{\text{sd}}_{a,y,k_y} = [[1:2],[4:4]]$.

Figure 2 shows how these variables change as a unit operates: start-up variable is 1 at the first block the unit is producing above 0, and shut-down variable is 1 at the first block that the unit is not producing anything in.

The following constraints were added to ensure that the variables have correct values. The variable $v^{\text{available units}}_{a,y}$ represents the amount of available units of asset a in year y. Constraints are defined $\forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{su}}_{a,f,y,k_y}$:

$$v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} - v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y}-1)} = v^{\text{start up}}_{a,k_y,b_{k_y}} - v^{\text{shut down}}_{a,k_y,b_{k_y}} \tag{1a}$$

$$v^{\text{start up}}_{a,k_y,b_{k_y}} \leq v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \tag{1b}$$

$$v^{\text{shut down}}_{a,k_y,b_{k_y}} \leq v^{\text{available units}}_{a,y} - v^{\text{units on}}_{a,k_y,B^{\text{uc}}_{a,y,k_y}(b_{k_y})} \tag{1c}$$

$$v^{\text{start up}}_{a,k_y,b_{k_y}}, \; v^{\text{shut down}}_{a,k_y,b_{k_y}} \in \mathbb{Z}_{\geq 0} \tag{1d}$$

2.5 New constraints

Before introducing SU/SD capabilities, some parameters are defined to represent the compound ramping of units throughout the time block. Explanation of the duration parameter can be found on the next page. Define $\forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{highest}} \setminus \{b^{\text{start}}\}$:

$$p_{a,y,k_y,b_{k_y}}^{\text{start up avg}} = \frac{1}{p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \sum_{0 \le i < p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \min(p_{a,y,k_y,b_{k_y}}^{\max},\ p_{a,y,k_y,b_{k_y}}^{\text{start up ramp}} + p_{a,y,k_y,b_{k_y}}^{\text{ramp up}} \cdot i) \tag{2a}$$

$$p_{a,y,k_y,b_{k_y}}^{\text{shut down avg}} = \frac{1}{p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \sum_{0 \le i < p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \min(p_{a,y,k_y,b_{k_y}}^{\max},\ p_{a,y,k_y,b_{k_y}}^{\text{shut down ramp}} + p_{a,y,k_y,b_{k_y}}^{\text{ramp down}} \cdot i) \tag{2b}$$

$$p_{a,y,k_y,b_{k_y}}^{\text{ramp up avg}} = \frac{1}{p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \sum_{1 \le i \le p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \min(p_{a,y,k_y,b_{k_y}}^{\max},\ p_{a,y,k_y,b_{k_y}}^{\text{ramp up}} \cdot i) \tag{2c}$$

$$p_{a,y,k_y,b_{k_y}}^{\text{ramp down avg}} = \frac{1}{p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \sum_{1 \le i \le p_{a,y,k_y,b_{k_y}}^{\text{duration}}} \min(p_{a,y,k_y,b_{k_y}}^{\max},\ p_{a,y,k_y,b_{k_y}}^{\text{ramp down}} \cdot i) \tag{2d}$$

The five SU/SD capability constraints below are based on the work of [14] and [15], but adapted by myself and the project supervisor to work with fully flexible temporal resolution. They are defined $\forall y \in \mathcal{Y}, a \in \mathcal{A}_y^{\text{uc}}, k \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}_{a,y,k_y}^{\text{highest}} \setminus \{b^{\text{start}}\}$:

$$\begin{aligned} v_{a,k_y,b_{k_y}}^{\text{flow total}} - v_{a,k_y,(b_{k_y}-1)}^{\text{flow total}} \le\ & v_{a,k_y,b_{k_y}}^{\text{start up}} \cdot (p_{a,y,k_y,b_{k_y}}^{\text{start up avg}} - p_{a,y,k_y,b_{k_y}}^{\min} - p_{a,y,k_y,b_{k_y}}^{\text{ramp up avg}}) \\ & + v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y})}^{\text{units on}} \cdot (p_{a,y,k_y,b_{k_y}}^{\min} + p_{a,y,k_y,b_{k_y}}^{\text{ramp up avg}}) \\ & - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y}-1)}^{\text{units on}} \cdot p_{a,y,k_y,b_{k_y}}^{\min} \end{aligned} \tag{3a}$$

$$\begin{aligned} v_{a,k_y,(b_{k_y}-1)}^{\text{flow total}} - v_{a,k_y,b_{k_y}}^{\text{flow total}} \le\ & v_{a,k_y,b_{k_y}}^{\text{shut down}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\text{shut down avg}} - p^{\min} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{ramp down avg}}) \\ & + v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y}-1)}^{\text{units on}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\min} + p_{a,y,k_y,(b_{k_y}-1)}^{\text{ramp down avg}}) \\ & - v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y})}^{\text{units on}} \cdot p_{a,y,k_y,(b_{k_y}-1)}^{\min} \end{aligned} \tag{3b}$$

$$\begin{aligned} v_{a,k_y,(b_{k_y}-1)}^{\text{flow total}} \le\ & v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y}-1)}^{\text{units on}} \cdot p_{a,y,k_y,(b_{k_y}-1)}^{\max} \\ & - v_{a,k_y,(b_{k_y}-1)}^{\text{start up}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\max} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{start up avg}}) \\ & - v_{a,k_y,b_{k_y}}^{\text{shut down}} \cdot \max(p_{a,y,k_y,(b_{k_y}-1)}^{\text{start up avg}} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{shut down avg}},\ 0) \end{aligned} \tag{3c}$$

$$\begin{aligned} v_{a,k_y,(b_{k_y}-1)}^{\text{flow total}} \le\ & v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y}-1)}^{\text{units on}} \cdot p_{a,y,k_y,(b_{k_y}-1)}^{\max} \\ & - v_{a,k_y,b_{k_y}}^{\text{shut down}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\max} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{shut down avg}}) \\ & - v_{a,k_y,(b_{k_y}-1)}^{\text{start up}} \cdot \max(p_{a,y,k_y,(b_{k_y}-1)}^{\text{shut down avg}} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{start up avg}},\ 0) \end{aligned} \tag{3d}$$

$$\begin{aligned} v_{a,k_y,(b_{k_y}-1)}^{\text{flow total}} \le\ & v_{a,k_y,B_{a,y,k_y}^{\text{uc}}(b_{k_y}-1)}^{\text{units on}} \cdot p_{a,y,k_y,(b_{k_y}-1)}^{\max} \\ & - v_{a,k_y,(b_{k_y}-1)}^{\text{start up}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\max} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{start up avg}}) \\ & - v_{a,k_y,b_{k_y}}^{\text{shut down}} \cdot (p_{a,y,k_y,(b_{k_y}-1)}^{\max} - p_{a,y,k_y,(b_{k_y}-1)}^{\text{shut down avg}}) \end{aligned} \tag{3e}$$

Constraints (3c) and (3d) are only used for time blocks in $\mathcal{B}^{\text{highest}}_{a,y,k_y}$ that exactly overlap with a UC block. Otherwise, and only then, (3e) is used.

The variable $v^{\text{flow total}}_{a,k_y,b_{k_y}}$ represents all the flows going out of an asset in each time block $b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y}$. Subscript $b_{k_y} - 1$ refers to the block before b_{k_y} in $\mathcal{B}^{\text{highest}}_{a,y,k_y}$. Finally, $p^{\text{duration}}_{b_{k_y}}$ represents the minimum length of the blocks of all flow variables in block b_{k_y}. For figure 1, if $b_{k_y} = [3:3]$, then $v^{\text{flow total}}_{a,k_y,3:4}$ is just $v^{\text{flow}}_{f,k_y,3:4}$, so $p^{\text{duration}}_{b_{k_y}} = 2$.

Start-up and shut-down variables may not exist for some b_{k_y}, this happens if $B^{\text{uc}}_{a,y,k_y}(b_{k_y}) = B^{\text{uc}}_{a,y,k_y}(b_{k_y} - 1)$. Then we assume values of these non-existing variables are 0. Because the SU/SD capabilities are defined for the hour that the unit is turning on, the current constraint formulation does not work for resolutions higher than 1h.

2.6 Correctness of the new constraints

Figures 3 and 4 will be used to illustrate why the constraints introduced in the last subsection correctly bound SU/SD capabilities.

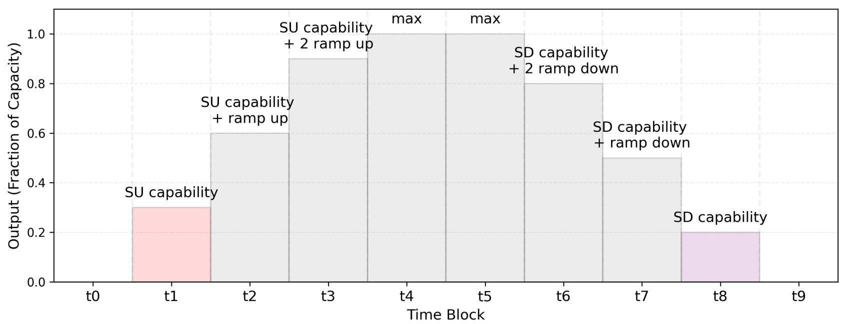


Figure 3: An asset turning on and off in the span of 10 hours, with $v^{\text{start up}} = 1$ for t1, and $v^{\text{shut down}} = 1$ for t9, $p^{\text{ramp up}} = p^{\text{ramp down}} = 0.3$, $p^{\text{start up ramp}} = 0.3$, $p^{\text{shut down ramp}} = 0.2$, $p^{\text{min}} = 0.1$, $p^{\text{max}} = 1$.

Example 1: hourly resolution for assets and flows. Here $p^{\text{start up avg}} = \min(p^{\text{max}}, p^{\text{start up ramp}}) = p^{\text{start up ramp}}$ and $p^{\text{shut down avg}} = p^{\text{shut down ramp}}$. Also $p^{\text{ramp up avg}} = \min(p^{\text{max}}, p^{\text{ramp up}}) = p^{\text{ramp up}}$, and $p^{\text{ramp down avg}} = p^{\text{ramp down}}$. The constraint that imposes the bound is indicated on each line.

- (3c): For t1, the flow is bound by $p^{\text{max}} - (p^{\text{max}} - p^{\text{start up ramp}}) = p^{\text{start up ramp}}$.
- (3d): For t8, the flow is bound by $p^{\text{max}} - (p^{\text{max}} - p^{\text{shut down ramp}}) = p^{\text{shut down ramp}}$.
- (3c)/(3d): For t2 through t7, the unit stays on, so the flow is bound by p^{max}.
- (3c)/(3d): For t0 and t9, the bound is 0.
- (3a): Flow differences t2 - t1, t3 - t2, t4 - t3, t5 - t4 are bound by $(p^{\text{min}} + p^{\text{ramp up avg}}) - p^{\text{min}} = p^{\text{ramp up avg}} = p^{\text{ramp up}}$.
- (3b): Flow differences t5 - t6, t6 - t7, t7 - t8 is at most $p^{\text{ramp down avg}} = p^{\text{ramp down}}$.
- (3a): t1 - t0 is bound by $(p^{\text{start up avg}} - p^{\text{min}} - p^{\text{ramp up avg}}) + (p^{\text{min}} + p^{\text{ramp up avg}}) = p^{\text{start up avg}} = p^{\text{start up ramp}}$.

- (3b): t8 - t9 is bound by $(p^{\text{shut down avg}} - p^{\min} - p^{\text{ramp down avg}}) + (p^{\min} + p^{\text{ramp down avg}}) = p^{\text{shut down avg}} = p^{\text{shut down ramp}}$.

Example 2: 4h uniform resolution for assets and flows. Assume there exist blocks tx before t0 and ty after t9, such that the partitions are [[tx : t0], [t1 : t4], [t5 : t8], [t9 : ty]]. Here $p^{\text{start up avg}} = \frac{1}{4}(p^{\text{start up ramp}} + (p^{\text{start up ramp}} + p^{\text{ramp up}}) + (p^{\text{start up ramp}} + 2 \cdot p^{\text{ramp up}}) + p^{\max})$, similar for $p^{\text{shut down avg}}$. Also $p^{\text{ramp up avg}} = \frac{1}{4}(p^{\text{ramp up}} + (2 \cdot p^{\text{ramp up}}) + (3 \cdot p^{\text{ramp up}}) + p^{\max})$, similar for $p^{\text{ramp down avg}}$.

- (3c): For [t1 : t4], the flow is bound by $p^{\max} - (p^{\max} - p^{\text{start up avg}}) = p^{\text{start up avg}}$, which makes sense, as that is exactly the average flow in [t1 : t4].
- (3d): For [t5 : t8], the flow is bound by $p^{\max} - (p^{\max} - p^{\text{shut down avg}}) = p^{\text{shut down avg}}$.
- (3a): Flow difference [t1 : t4] - [tx : t0] is bound by $p^{\text{ramp up avg}}$.
- (3b): Flow difference [t5 : t8] - [t9 : ty] is bound by $(p^{\text{shut down avg}} - p^{\min} - p^{\text{ramp down avg}}) + (p^{\min} + p^{\text{ramp down avg}}) = p^{\text{shut down avg}}$.
- (3b): Flow difference [t1 : t4] - [t5 : t8] is bound by $p^{\text{ramp down avg}}$.
- (3a): Flow difference [t5 : t8] - [t1 : t4] is bound by $p^{\text{ramp up avg}}$.

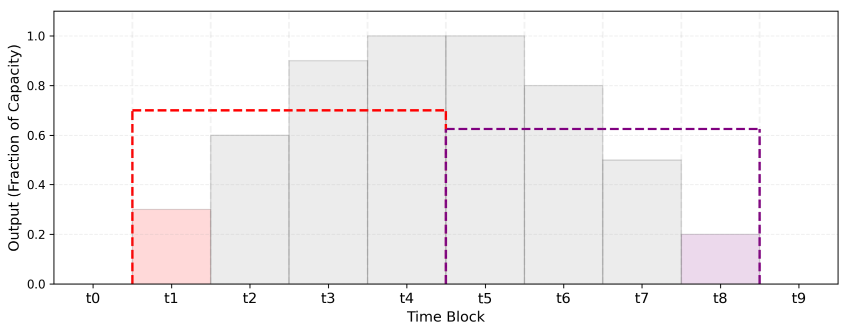


Figure 4: Figure 3 updated for 4h resolution, dashed lines show flows for [t1, t4], [t5, t8].

Example 3: 8h asset resolution and 4h flow resolution. Assume for the asset the partition [[tz : t0], [t1 : t8], [t9 : tw]], for the flow [[tx : t0], [t1 : t4], [t5 : t8], [t9 : ty]]. Parameters $p^{\text{start up avg}}$, $p^{\text{shut down avg}}$, $p^{\text{ramp up avg}}$, $p^{\text{ramp down avg}}$ stay the same.

- (3e): For [t1 : t4], the flow is still bound by $p^{\text{start up avg}}$, and [t5 : t8] still by $p^{\text{shut down avg}}$.
- (3a):/(3b): Flow differences stay the same.

3 Experimental Setup and Results

This section describes the case study and the data used for it (subsection 3.1), the setup of the experiments (subsection 3.2) and the results obtained (subsection 3.3).

3.1 Case studies

The effect of implementing the constraints introduced in section 2 was assessed by running a case study that modelled the electricity grid of 7 countries: the Netherlands, Belgium, Germany, France, Luxembourg, Switzerland, and Austria. Assets available for investments included coal and nuclear power plants, open cycle gas turbines (OCGTs), combined cycle gas turbines (CCGTs), onshore and offshore wind farms, solar farms, battery grid connections, and battery storage. It was an important part of this research to make the data as realistic as possible within the available time window, so existing papers and datasets were used to generate the final dataset:

- Countries and their connections, peak demands for countries: [7];
- Availability profiles for assets, demand profile time series: personal communication with TNO researchers working on Tulipa;
- Capacities for assets: averaged from [17]; investment costs for assets: [18];
- Minimum operating point for assets: [19]; MWh cost for assets: [20].

The countries were allowed to trade electricity with geographically neighbouring ones at a limited capacity and at no cost. Initial units for each asset and country were set to 0, which is not realistic, but was done with the goal of exploring the GEP part of Tulipa and seeing what assets get invested into. Further limitations are described in section 4, and the full dataset can be found in [21].

3.2 Experimental setup

The model considered a 1 year timespan with 10 representative periods of 24 hours. For temporal resolutions, the following were used:

- 1h/2h/3h/4h uniform;
- 2h uniform for assets and 1h uniform for flows ("2+1h");
- 4h uniform for assets and 2h uniform for flows ("4+2h");
- 3h uniform for assets and 2h uniform for flows ("3+2h");
- 4h uniform for assets and 3h uniform for flows ("4+3h").

For each of the resolutions, two cases were created: one that includes only UC constraints available in Tulipa (version 0.15.0) before this research, and one that also includes the new constraints for these types of assets: CCGT, OCGT, coal and nuclear power plants. In total, 16 cases were considered. Even though the cases where the asset resolution is not a multiple of the flow resolution are not necessarily very practical or realistic, it is interesting to explore them from the perspective of fully flexible temporal resolution.

Each of the cases was executed 50 times with randomised seeds to see the variance in runtime. The Gurobi solver [22] was used to solve the model created by JuMP [23], and BenchmarkTools [24] for Julia was utilised for measurements. Time to create the model, as well as the time to solve the model (excluding creation time) were tracked. The tables created as part of the last run were saved to see the change in variable assignment, together with the objective function value, and the random seeds used to choose the solving path.

The experiments were executed on a Lenovo Legion 5 Pro 16ACH6H personal laptop running Kubuntu 24.04, CPU model being AMD Ryzen 7 5800H with Radeon Graphics, 8 physical cores and 16 logical processors, using up to 16 threads.

3.3 Results

This subsection illustrates and shortly describes the main results of running the case study. The interpretation of these results can be found in section 4.

Figure 5 shows the solving times and creation times of the model before and after adding the new constraints. In this figure, as well as other figures and tables in this paper, *"basic"* is the name of the case excluding SU/SD capabilities, *"su_sd"* is the case including them. Both the solving and the creation of the model take longer when the new constraints are present, with the exception of solving time for "4+2h" and "4+3h" resolutions. Notably, cases for which the asset resolution is not a multiple of the flow resolution take significantly longer to solve than other cases. The exact runtimes can be found in appendix B.

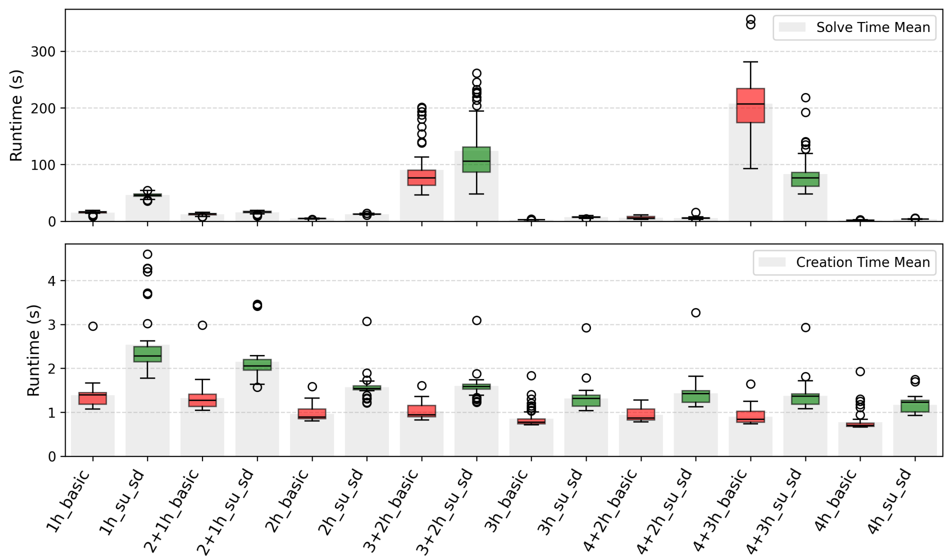


Figure 5: Times of solving (top) and creating (bottom) the model for all resolutions.

Table 2 shows that the objective function value is consistently higher when including the new constraints, and and the difference is significant, i.e. not within the MIP gap of 0.01%. Furthermore, cases with lower resolutions - more specifically, less detailed $\mathcal{B}^{\text{highest}}$ - tend to have lower objective function values, both with and without SU/SD capabilities.

Scenario	**basic**	**su_sd**	**% difference**
1h	63,029,875	63,052,376	0.03570%
2+1h	62,957,414	63,007,553	0.07964%
2h	62,822,680	62,866,889	0.07037%
3+2h	62,905,930	62,967,213	0.09742%
3h	62,517,080	62,619,569	0.16394%
4+2h	62,616,085	62,757,851	0.22641%
4+3h	62,787,216	62,798,480	0.01794%
4h	62,276,802	62,432,080	0.24934%

Table 2: Objective value comparison in kEUR, rounded to integer.

Figure 6 highlights that investment decisions recommended by the solver before and after introducing the new constraints are mostly similar. Assets that are invested more into are batteries (both grid connection and storage capacities) and CCGTs, while OCGTs are invested into less. Solar, onshore wind, and coal plants experience minor changes. Nuclear and offshore wind assets are never used. These findings are consistent for all resolutions.

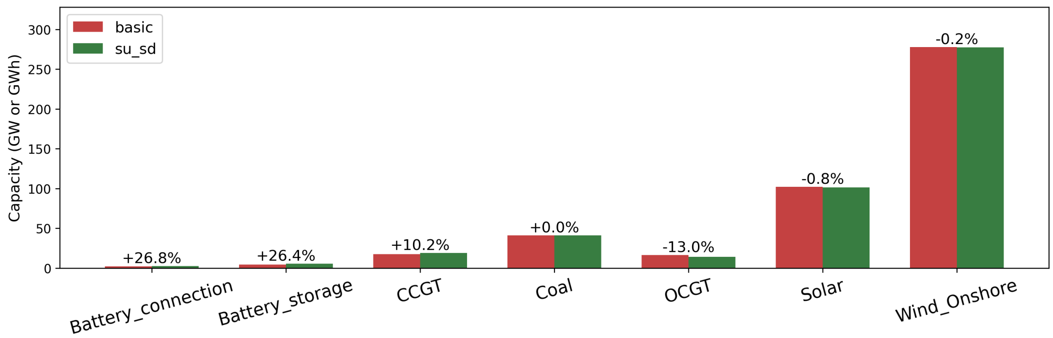


Figure 6: Investments under 2h uniform resolution.

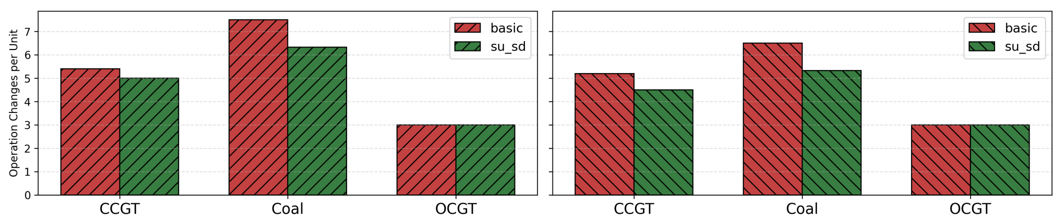


Figure 7: Number of times per unit of starting up (left) and shutting down (right), for 3h uniform resolution.

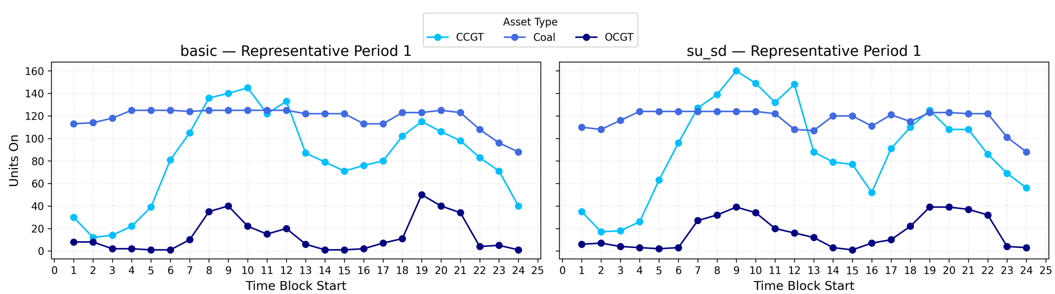


Figure 8: Numbers of units that are on at each timestep, using 1h uniform resolution.

The number of times units with SU/SD constraints get turned on and off shrinks for most assets and resolutions, as seen in figure 7. The difference is more pronounced for high resolutions. The general trend of operation for the units with the new constraints follows a similar trajectory before and after adding the new constraints, example of which can be seen in figure 8.

4 Discussion

This section interprets the findings presented in section 3 (subsections 4.1-4.3), and comments on the ethical implications and reproducibility (subsection 4.4).

4.1 Computation time

Creation time of the model increases after introducing SU/SD capabilities (figure 5), this is because it is time-consuming to add more variables and constraints to the model. The solving time goes up in most cases, which is likely due to the fact that more constraints and variables are now present. However, for "4+2h" and "4+3h" resolutions, adding the SU/SD capabilities decreases the solving time, perhaps because the feasible solution space is now reduced, and as such the optimal variable assignment could be discovered earlier.

It is not immediately clear why "3+2h" and "4+3h" resolutions take significantly longer to solve. Since these are the only cases where the block length in $\mathcal{B}^{\text{highest}}$ is not the same throughout the representative period, it could be that the solver cannot branch as effectively as when there is a set block length. It is evident that using these resolutions is impractical compared to other resolutions, even those that are very detailed, such as hourly. Interestingly, this situation does not occur if the countries in the model are not allowed to trade with each other. In that case, the solving time gets progressively lower as the resolution is reduced. However, the case without trade is not realistic, as it is effectively solving many small separate models, so it is not explored further in this research.

4.2 Objective function value

Even though the model is meant to represent the real world, it has to make simplifications that increase the apparent flexibility of the assets. Thus, the objective function value produced by the solver is likely an underestimation of real costs. Since the actual costs are not known, the solution of 1h uniform resolution is taken to be the representative value.

It can be seen in table 2 that the values in the column without the new constraints are consistently lower. That is because adding the new constraints reduces the flexibility of the generators, and more costs may be incurred when scheduling less freely. Furthermore, it can be seen that reducing the resolution underestimates the real values more, both with and without the added constraints. Having a more complex resolution underestimates the costs less than a comparable uniform resolution, e.g., "3+2h" compared to 2h and 3h uniform resolutions. These observations are likely be due to the fact that $\mathcal{B}^{\text{highest}}$ in those cases is more detailed than in the uniform case, and the new constraints are defined for $\mathcal{B}^{\text{highest}}$.

4.3 Model variable values

The investment decisions are similar with and without the new constraints (figure 6). This is potentially due to the large scale of the model. With 7 countries capable of trading, the reduced flexibility of the generators can likely be circumvented mostly by adapting when, where, and at what capacity they operate. This suggests that the new constraints could have a more noticeable impact for a smaller model. Analysing figure 6 further suggests that investing more in batteries is helping the model to regain flexibility. From the assets with the new constraints, CCGTs increase in quantity, while OCGTs decrease - that is likely because CCGTs have the highest capabilities for start-up and shut-down out of all of the assets that get invested into, and are thus more flexible in that regard, while OCGTs have the lowest ones.

In terms of operation, the high-level trajectory of how many units are on at which time block tends to stay similar. This is in line with the earlier observation of investments staying mostly the same, and is probably also due to the large scale of the model. In addition, after adding SU/SD capabilities, units tend to be turned on and off a little less often (figure 7). This is not unexpected, as start-up and shut-down are more constrained than before.

In most cases, after adding the SU/SD capabilities, the assets that have these capabilities display one of the three patterns. Sometimes they operate shorter and produce less, as it is probably no longer economically advantageous for them to be running. In other cases, they operate longer and produce more, perhaps because they are covering for a less flexible asset. Alternatively, they operate for longer and produce less, likely because of their reduced capacities while starting up or shutting down. However, in the small number of remaining cases, an asset type (e.g., coal for a 2h uniform resolution) operated shorter and produced more (figure 9). A possible explanation is that without SU/SD capabilities it was not necessary to operate at full capacity at all times, and operating at a lower capacity saves fuel costs. However, with SU/SD capabilities included, excess energy might be produced, but stored in batteries to provide flexibility later.

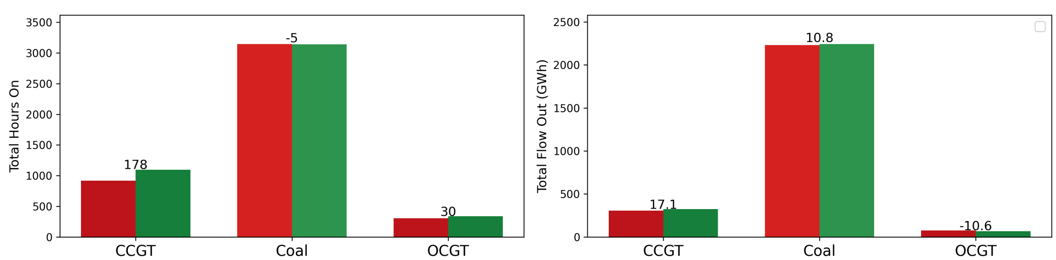


Figure 9: Differences in how long assets with UC constraints were on (left) and in the flow they produced (right) for 2h uniform resolution.

4.4 Responsible research

It is important to acknowledge the potential ethical implications of the work done during the project. Since Tulipa can be used to inform energy policy, there are two related considerations to make.

- Firstly, the correctness of the new constraints is important to assess. This was done by extensively discussing the formulations with the supervisor and examining the constraints generated by Tulipa when solving a model, both manually and using automated visualisations. Furthermore, subsection 2.6 was included in the paper to illustrate that the constraints work as expected for simple examples.

- Secondly, the added constraints could impact the types of assets suggested for investments, for example, make it more likely to invest into non-renewable technology. However, notably, the start-up and shut-down capability constraints that were added simply model the behaviour of generators more accurately. Based on the data collected, these capabilities are mostly important for gas plants, coal plants, and nuclear reactors. Making these less flexible in the model should keep the generation mix stable or maybe even promote using solar and wind farms in some cases, as they do not have SU/SD constraints. To further ensure renewable energy is prioritised even while the goal of the model is to find a solution with minimal costs, it is possible to set investment limits for non-renewable energy or to change the objective function to consider costs of emissions.

It was also an important part of this project to execute the research responsibly. To make sure the research done is reproducible, the data used in the case study is open-source and made publicly available (see [21]), including data obtained through personal communication. The benchmarking file and the resulting solutions are also available in the same repository, including the seeds used. Since Tulipa and Julia are also both open-source software, this should provide interested parties with the capability of reproducing the case study. Gurobi solver is a paid product, but can be replaced by HiGHS, a free alternative. To enhance replicability, the case studies were made as realistic as possibile, while also considering many different cases of temporal resolutions. Benchmarking was done 50 times to obtain representative computation times.

5 Conclusions and Future Work

This research formulated start-up and shut-down (SU/SD) capability constraints for a fully flexible temporal resolution and investigated how they affect the computation time and the optimal solution of the Tulipa energy model. Based on the results of a case study involving 7 European countries and 8 differing temporal resolutions, it can be concluded that adding the new constraints makes the computation time generally longer for creating, as well as for solving the model. Runtime for cases where the asset resolution is not a multiple of the flow resolution was unusually high both when excluding and including SU/SD capabilities, so it can be better to use an hourly resolution for most purposes. Including the new constraints makes the model more accurate by reducing the feasible solution space. Since the flexibility of the system is underestimated less, the objective function value becomes higher. In addition, decreasing the resolution makes the objective function value lower, both with and without SU/SD capabilities. The investments that the solver suggests change only slightly when introducing the new constraints, showing a small increase in battery and CCGT use, and a comparable decrease in OCGT use. The units that the capabilities are introduced for tend to get turned on and off less. However, the high-level overview of the number of units operating throughout a representative period shows minimal changes. Overall, including SU/SD capabilities comes at a cost of increased runtime, but slightly improves model accuracy.

Two main limitations of the research were the time horizon in the model and excluding hydrogen demand. Firstly, to reduce the runtime of solving the model, the case study only encompassed one milestone year. Experiments were conducted to see if it is feasible to model multiple years, however, the runtime sharply increased, and the findings seemed similar to those of a one-year study. Secondly, even though Tulipa is capable of also modelling hydrogen demand alongside electricity, it was not considered within the study, as the scope was limited by project duration.

Having in mind these limitations, some interesting future work directions can be formulated. The first one would be extending the case study to multiple years or decades, which would show how SU/SD capabilities affect the solution on a longer term. Another direction would be adding the hydrogen demand into the model, while the most realistic case study would unite both the inclusion of hydrogen and the expansion of the time horizon. Alternatively, looking further into the reason behind the massive runtime increase for cases where the asset resolution is not a multiple of the flow resolution would provide more insight into the effect of using fully flexible time resolution.

Acknowledgements

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A Additional Mathematical Formulas

Parameter	Meaning
$p^{\text{availability profile}}_{a,y,k_y,b_{k_y}}$	Specifies if the units of asset a are available or not in block b_{k_y}, representative period k_y, year y.
p^{capacity}_{a}	The capacity of an asset a.
$p^{\text{min operating point}}_{a,y}$	The minimum operating point as a fraction of total capacity for asset a in year y.
$p^{\text{max ramp up}}_{a,y}$	Maximum ramping up of asset a in year y.
$p^{\text{max ramp down}}_{a,y}$	Maximum ramping down of asset a in year y.
$p^{\text{max start up ramp}}_{a,y}$	Maximum start-up capability of asset a in year y.
$p^{\text{max shut down ramp}}_{a,y}$	Maximum shut-down capability of asset a in year y.

Table 3: Input parameters used to define more complex parameters.

The formulas below use the general parameters from table 3 to build the more complex parameters used in start-up/shut-down capability constraints. These formulas are defined $\forall y \in \mathcal{Y}, a \in \mathcal{A}^{\text{uc}}_y, k_y \in \mathcal{K}_y, b_{k_y} \in \mathcal{B}^{\text{highest}}_{a,y,k_y}$:

$$p^{\text{max}}_{a,y,k_y,b_{k_y}} = p^{\text{availability profile}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{capacity}}_{a} \tag{4a}$$

$$p^{\text{min}}_{a,y,k_y,b_{k_y}} = p^{\text{max}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{min operating point}}_{a,y} \tag{4b}$$

$$p^{\text{ramp up}}_{a,y,k_y,b_{k_y}} = p^{\text{max}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{max ramp up}}_{a,y} \tag{4c}$$

$$p^{\text{ramp down}}_{a,y,k_y,b_{k_y}} = p^{\text{max}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{max ramp down}}_{a,y} \tag{4d}$$

$$p^{\text{start up ramp}}_{a,y,k_y,b_{k_y}} = p^{\text{max}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{max start up ramp}}_{a,y} \tag{4e}$$

$$p^{\text{shut down ramp}}_{a,y,k_y,b_{k_y}} = p^{\text{max}}_{a,y,k_y,b_{k_y}} \cdot p^{\text{max shut down ramp}}_{a,y} \tag{4f}$$

B Exact numerical results

Tables 4 and 5 show the runtimes of results presented in a boxplot in section 3.

Run name	Average	Std.Dev.	Run name	Average	Std.Dev.
1h_basic	15.20	2.63	1h_su_sd	46.26	3.85
2+1h_basic	12.47	1.94	2+1h_su_sd	16.07	2.27
2h_basic	4.91	0.61	2h_su_sd	12.67	0.69
3+2h_basic	90.77	43.08	3+2h_su_sd	124.30	55.82
3h_basic	2.70	0.33	3h_su_sd	7.36	1.10
4+2h_basic	6.46	2.42	4+2h_su_sd	5.70	1.87
4+3h_basic	207.58	51.26	4+3h_su_sd	83.29	33.92
4h_basic	1.89	0.36	4h_su_sd	4.02	0.44

Table 4: Computation time (average and standard deviation) comparison of solving the model, in seconds, rounded to 2 decimal places. The larger of the two values is highlighted in green.

Run name	Average	Std.Dev.	Run name	Average	Std.Dev.
1h_basic	1.38	0.28	1h_su_sd	2.54	0.69
2+1h_basic	1.32	0.29	2+1h_su_sd	2.15	0.41
2h_basic	0.96	0.16	2h_su_sd	1.57	0.25
3+2h_basic	1.02	0.17	3+2h_su_sd	1.60	0.25
3h_basic	0.86	0.21	3h_su_sd	1.32	0.28
4+2h_basic	0.94	0.15	4+2h_su_sd	1.43	0.31
4+3h_basic	0.90	0.18	4+3h_su_sd	1.37	0.28
4h_basic	0.78	0.22	4h_su_sd	1.17	0.17

Table 5: Computation time (average and standard deviation) comparison of creating the model, in seconds, rounded to 2 decimal places. The larger of the two values is highlighted in green.

References

[1] Utsav Bhattarai, Tek Maraseni, and Armando Apan. "Assay of renewable energy transition: A systematic literature review". In: *Science of The Total Environment* 833 (Aug. 2022), p. 155159. ISSN: 0048-9697. DOI: 10.1016/j.scitotenv.2022.155159. URL: https://www.sciencedirect.com/science/article/pii/S0048969722022525 (visited on 04/27/2025).

[2] 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).

[3] 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).

[4] 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. URL: https://link.springer.com/10.1007/s12667-023-00564-5 (visited on 04/23/2025).

[5] 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.

[6] Holger Teichgraeber. "Time-series aggregation for the optimization of energy systems: Goals, challenges, approaches, and opportunities". en. In: *Renewable and Sustainable Energy Reviews* (2022).

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

[8] Laura C Brafine. "Exploring the Potential of Down-Sampling to Reduce Temporal Resolution in Energy System Optimisation Models". en. In: (Sept. 2024).

[9] 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).

[10] *Tulipa*. en. URL: https://github.com/TulipaEnergy (visited on 04/27/2025).

[11] Bryan S. Palmintier and Mort D. Webster. "Heterogeneous Unit Clustering for Efficient Operational Flexibility Modeling". en. In: *IEEE Transactions on Power Systems* 29.3 (May 2014), pp. 1089–1098. ISSN: 0885-8950, 1558-0679. DOI: 10.1109/TPWRS.2013.2293127. URL: http://ieeexplore.ieee.org/document/6684593/ (visited on 04/25/2025).

[12] 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).

[13] Diego A Tejada-Arango et al. “Enhanced Representative Days and System States Modeling for Energy Storage Investment Analysis”. en. In: (Nov. 2018).

[14] 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. URL: http://link.springer.com/10.1007/s10107-015-0919-9 (visited on 04/23/2025).

[15] C Gentile, G Morales-España, and A Ramos. “A Tight MIP Formulation of the Unit Commitment Problem with Start-up and Shut-down Constraints”. en. In: (Aug. 2014).

[16] 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. URL: http://ieeexplore.ieee.org/document/7521298/ (visited on 04/25/2025).

[17] *Global Power Plant Database - Datasets*. en. URL: https://datasets.wri.org//datasets/global-power-plant-database (visited on 05/31/2025).

[18] *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).

[19] *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).

[20] *IEA-ETSAP | Energy Supply Technologies Data*. URL: https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data (visited on 05/31/2025).

[21] Rūta Giedrytė. *RutaGiedryte/su-sd-ramping-case-studies: The data used for case studies that evaluate the effect of introducing start-up and shut-down constraints to Tulipa energy model*. en. URL: https://github.com/RutaGiedryte/su-sd-ramping-case-studies (visited on 06/11/2025).

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

[23] Iain Dunning, Joey Huchette, and Miles Lubin. “JuMP: A Modeling Language for Mathematical Optimization”. en. In: *SIAM Review* 59.2 (Jan. 2017), pp. 295–320. ISSN: 0036-1445, 1095-7200. DOI: 10.1137/15M1020575. URL: https://epubs.siam.org/doi/10.1137/15M1020575 (visited on 06/02/2025).

[24] *JuliaCI/BenchmarkTools.jl*. original-date: 2016-02-23T20:54:02Z. May 2025. URL: https://github.com/JuliaCI/BenchmarkTools.jl (visited on 06/07/2025).