Operational flexibility provided by storage in generation expansion planning with high shares of renewables

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***Abstract*—The integration of variable renewable energy resources result in an increased need for operational flexibility. Energy storage is one of the alternatives to conventional generation technologies to provide this flexibility. A generic model for energy storage is introduced into a generation expansion planning model, considering operational constraints of power plants and system balancing requirements. Different targets for the final renewable electricity generation towards the future are imposed, quantifying the need for electricity storage and the impact on the electricity generation mix. When facing high renewable targets, storage is found to reduce the need for installed generation capacity, both conventional and renewable, and reduce the electricity generation costs.**

***Index Terms* – Electricity storage, generation expansion modeling, power system planning, operating reserves, renewable generation.**

I. INTRODUCTION

Decarbonizing the electricity sector is pursued by means of increasing the share of Renewable Energy Sources (RES) in the electricity generation. In many countries, this translates in renewable targets which are met by substantial growth in wind and photovoltaic (PV) power. However, the intermittent nature of these generation sources challenges the cost-efficient and reliable operation of the power system [1], [2]. Their variable output and limited predictability result in a need for back-up generation capacity and balancing services [3]. Consequently, increased operational flexibility is required, i.e. capacity which can be rapidly regulated up- or downward, in order to keep the total injection in balance with the off-take [4].

Short-term power system models, such as unit commitment models and economic dispatch models (UCED), allow to calculate the impact of the integration of variable RES on the scheduling and dispatch of power plants. In addition, long-term power system models, such as generation expansion models (GEPs) allow to determine the optimal investments in the generation mix. Both models are therefore a useful tool to study the optimal generation mix meeting the targeted renewable capacities, as well as it optimal operation. However, GEPs typically consider a lower temporal resolution and a less detailed representation of the operational constraints of the power system. This has been shown to result in (1) an overestimation of the uptake of renewable energy, (2) an underestimation of operational costs and (3) suboptimal investments in generation capacity, possibly resulting in a generation portfolio which might not cope well with RES variability [5], [6].

Therefore, a new GEP model is developed which considers detailed operational constraints and therefore captures the operational challenges of integrating variable RES when optimizing a generation portfolio [5]. It was shown that the operating reserve requirements to balance unexpected power deviations resulting from forecast errors have a strong impact on the feasibility of the targeted RES, certainly when operating reserve procurement is limited to conventional generation capacity. As the share of this conventional generation capacity in the generation mix diminishes, an important emphasis needs to be put on alternative sources of flexibility, such as demand response and electricity storage, for the provision of balancing services. This paper examines which role electricity storage can play as a provider of operational flexibility in the future electricity system characterized by high shares of RES.

Much research has already been conducted on the future need and role for energy storage, specifically with regards to the integration of increasing amounts of renewable energy. For instance, some studies have adopted an analytic approach to study the benefits of storage from a utility's point of view. By decomposing the balancing problem in periodic components (daily, hourly, minutely), the maximum energy storage requirements are determined at different time-scales [7], [8]. Other studies have analyzed the role of energy storage using UCED models, considering both the use of storage for the energy market and operating reserves [9], [10]. They point out the lack of incentives for flexibility provided by the energy-only market which results in limited investment in energy storage. However, it is shown that storage can offer greater value providing ancillary services, i.e. operating reserves. Some studies move to shorter time horizons, such as 15 minutes, to better capture the short-term constraints of power systems, such as the conventional plants' cycling behavior, better showing the potential for storage to valorize its flexibility [11].

This paper considers the use of storage for the energy-market, as well as operating reserves, with a distinction between the different types of operational reserves. It adds to the literature by not only evaluating the added value of storage for short-term operational reliability, as is done with UCED models, which typically consider a time-horizon of only 24h-48h, but by also evaluating the added value of storage for long-term reliability, i.e. generation adequacy. Furthermore, this paper investigates how the optimal generation portfolio changes when storage is available as an investment alternative to conventional generation capacity. This allows to quantify the need for electrical storage, as well as its impact on the electricity generation mix composition. This allows to better estimate the integration costs of RES, and help with determining the optimal future generation mix.

Section II presents the methodology, including the expanded GEP model with a generic model of energy storage and the conceptual test system. Section III discusses the results. Finally, in Section IV conclusions are drawn and opportunities for future work elaborated.

II. METHODOLOGY

A. Generation Expansion Planning model

To study the influence of energy storage as a source of operational flexibility – an alternative to conventional generation capacity – storage is integrated in an existing GEP model [5]. This model calculates the optimal installed generation capacity of a system by means of a linear total cost minimization. The operational costs are calculated with help of a linear technology-clustered formulation of the unit commitment problem, which allows for the inclusion of very detailed operational constraints (minimum up and down times, ramping capability at different time scales, etc.). Thus, the model considers both the investment phase and the scheduling of generation and reserve power, while real time is not considered. Solving this model results in the optimal installed capacities, generation levels and scheduling of reserve power.

A generic model of energy storage is now introduced, considering the main technical parameters of storage technology, namely: energy [MWh], power [MW], ramping capability and round-trip efficiency [%]. The storage can be used to optimize the scheduling of conventional generation to meet a fixed demand, as well as participate in the operating reserve requirements set by the Transmission System Operator (TSO). At present the model does not consider grid constraints. The model does allow for separate investments in energy and power capacity to more accurately match the system's needs.

The introduction of storage has implications for the objective function, the balance equation as well as the reserve power equations. Additionally, a new set of equations is introduced to describe the operational behavior of the storage.

The objective function calculates the total system cost, including the investment costs, the fixed operating and maintenance costs, the fuel costs, the variable operating and maintenance costs, the ramping costs, the start-up costs, the energy cost and the power cost of storage and, finally, the cost of lost load.

The balance equation ensures that supply equals demand $DEM(t)$ at every time step t. Load shedding $ls(t)$ is allowed at the cost of lost load. Curtailment is also allowed. The electricity generation is represented by the variables $gen(g,t)$ and $gen(r,t)$ for the conventional generation technologies g and the renewable generation technologies r respectively. Charging and discharging of the storage technology are represented by the variables $p_c(t)$ and $p_d(t)$ respectively.

$$\forall\ t \qquad \begin{gathered}\textstyle\sum_g gen(g,t) + \sum_r gen(r,t) + p_d(t) = \\ DEM(t) + p_c(t) - ls(t)\end{gathered} \tag{1}$$

To ensure operational reliability, reserve power constraints are included. For this work the forecast errors of variable RES generation are considered as a driver of system imbalances. As the influence of variable RES on the second-minute time scale is not expected to have an important impact on the operation of the system [12], the focus is on the automatic and manual Frequency Restoration Reserves (aFRR, mFRR) – formerly known as the secondary and fast tertiary reserves – as defined by the European Network of Transmission System Operators for Electricity (ENTSO-E) in its Network Code on Load-Frequency Control and Reserves [13]. The need for reserves is calculated endogenously, as it depends on the installed capacity of the variable RES. The calculation is static – meaning the same amount of reserves is held for the entire considered period; and probabilistic – meaning that the stochastic nature of the forecast errors is taken into account. As such, a need for up- and downward aFRR and mFRR is formulated, captured by the variables q_{afrr}^{up}, q_{afrr}^{dn}, q_{mfrr}^{up} and q_{mfrr}^{dn} respectively.

Reserve power can be provided both by conventional generation technologies and storage. For the conventional generation technologies, this is represented by the variables $res_{afrr}^{up}(g,t)$, $res_{afrr}^{dn}(g,t)$, $res_{mfrr}^{up}(g,t)$, $res_{mfrr}^{dn}(g,t)$. For storage a distinction is made between charging and discharging, as these are considered independent operations. The reserve provision is represented by the variables $res_{afrr,c}^{up}(t)$, $res_{afrr,c}^{dn}(t)$, $res_{mfrr,c}^{up}(t)$ and $res_{mfrr,c}^{dn}(t)$ for charging and $res_{afrr,d}^{up}(t)$, $res_{afrr,d}^{dn}(t)$, $res_{mfrr,d}^{up}(t)$ and $res_{mfrr,d}^{dn}(t)$ for discharging.

$$\forall\ t \qquad \begin{gathered}\textstyle\sum_g res_{afrr}^{up}(g,t) + res_{afrr,c}^{up}(t) + \\ res_{afrr,d}^{up}(t) = q_{afrr}^{up}\end{gathered} \tag{2}$$

$$\forall\ t \qquad \begin{gathered}\textstyle\sum_g res_{afrr}^{dn}(g,t) + res_{afrr,c}^{dn}(t) + \\ res_{afrr,d}^{dn}(t) = q_{afrr}^{dn}\end{gathered} \tag{3}$$

$$\forall t \qquad \sum_g res^{up}_{mfrr}(g,t) + res^{up}_{mfrr,c}(t) + res^{up}_{mfrr,d}(t) = q^{up}_{mfrr} \tag{4}$$

$$\forall t \qquad \sum_g res^{dn}_{mfrr}(g,t) + res^{dn}_{mfrr,c}(t) + res^{dn}_{mfrr,d}(t) = q^{dn}_{mfrr} \tag{5}$$

Next, the set of equations describing the operational behavior of the storage technology is discussed. An energy balance describing the evolution of the energy level $e(t)$ is formulated, as well as a constraint limiting the energy level to the installed energy capacity $E(s)$. Here $\eta(s)$ is the round-trip efficiency of the storage technology.

$$\forall t \qquad e(t+1) = e(t) + p_c(t) \cdot \sqrt{\eta(s)} - \frac{p_d(t)}{\sqrt{\eta(s)}} \tag{6}$$

$$\forall t \qquad e(t) \le E(s) \tag{7}$$

Subsequently two equations are introduced regulating the evolution of the charging and discharging levels:

$$\forall t \qquad p_c(t+1) = p_c(t) + ramp_{up,c}(t) - ramp_{dn,c}(t) \tag{8}$$

$$\forall t \qquad p_d(t+1) = p_d(t) + ramp_{up,d}(t) - ramp_{dn,d}(t) \tag{9}$$

The variables $ramp_{up,c}(t)$, $ramp_{dn,c}(t)$, $ramp_{up,d}(t)$ and $ramp_{dn,d}(t)$ represent the up- and downward changes in the charging and discharging levels. These variables are important when evaluating the ramping ability of the storage technology. This ability is also addressed for the provision of reserves. Consider the discharging process. In total the actual discharging, scheduled increase in discharging (represented by $ramp_{up,d}(t)$) and provision of upward reserves (also an increase in discharging) is limited by the power capacity of the storage unit $P(s)$. Conversely, the decrease in discharging (represented by $ramp_{dn,d}(t)$) and the provision of downward reserves is limited by the actual discharging level. A similar reasoning holds for the charging process, leading to the following constraints:

$$\forall t \qquad p_d(t) + ramp_{up,d}(t) + res^{up}_{afrr,d}(t) + res^{up}_{mfrr,d}(t) \le P(s) \tag{10}$$

$$\forall t \qquad ramp_{dn,d}(t) + res^{dn}_{afrr,d}(t) + res^{dn}_{mfrr,d}(t) \le p_d(t) \tag{11}$$

$$\forall t \qquad p_c(t) + ramp_{up,c}(t) + res^{dn}_{afrr,c}(t) + res^{dn}_{mfrr,c}(t) \le P(s) \tag{12}$$

$$\forall t \qquad ramp_{dn,c}(t) + res^{up}_{afrr,c}(t) + res^{up}_{mfrr,c}(t) \le p_c(t) \tag{13}$$

Finally, storage differs inherently from conventional generation technologies when it comes to supplying reserves, because the energy it can provide is limited. As the operating reserves have to be online for a certain amount of time once activated, this has to be taken into account when offering reserve power. Therefore, (7) – the upper boundary of the energy level $e(t)$ – has to be made more stringent and an additional equation for the lower boundary of the energy level has to be introduced. Here T_{MARKET}, T_{AFRR} and T_{MFRR} are the time step of the market and the requested duration of delivery of the automatic and manual FRR.

$$\forall t \qquad \left(p_d(t) \cdot T_{MARKET} + res^{up}_{afrr,d}(t) \cdot T_{AFRR} + res^{up}_{mfrr,d}(t) \cdot T_{MFRR}\right) \cdot \frac{1}{\sqrt{\eta(s)}} \le e(t) \tag{14}$$

$$\forall t \qquad \left(p_c(t) \cdot T_{MARKET} + res^{dn}_{afrr,c}(t) \cdot T_{AFRR} + res^{dn}_{mfrr,c}(t) \cdot T_{MFRR}\right) \cdot \sqrt{\eta(s)} + e(t) \le E(s) \tag{15}$$

No ramping constraints are formulated for the dynamic ramping abilities of the storage. The smallest time step considered is that of the aFRR constraints, within which storage technologies can easily mobilize their entire rated charging power.

B. Data

The model is now applied to a conceptual test system. Four representative conventional generation technologies are selected; *Base*, *Mid*, *Peak* and *High Peak* technology[1] as well as two variable RES technologies are selected; PV and Wind.

Their technical and economic parameters were already presented in [5]. The technical parameters are based on the report of the Deutsches Institut für Wirtschaftforschung (DIW) on *Current and Prospective Costs of Electricity Generation until 2050* [14]. The economic parameters are based on the JRC-EU-TIMES model [15] for the year 2020.

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[1] The parameters of the *Base*, *Mid*, *Peak* and *High Peak* technology are based on the parameters of the *Nuclear*, *Coal New SuperC*, *Gas CC* and *Gas GT* technologies of the DIW report.

PV and wind production profiles from the year 2013 are gathered from the Belgian TSO [16]. To ensure a correct correlation between the meteorological data of the demand profile and the RES production profiles, the demand of the system is represented by the 2013 demand profile of the Belgian power system, which is gathered from ENTSO-E. The profile is rescaled such that the system has a peak power demand of 10 GW. This results in an annual consumption of 64 TWh. Cost of curtailment is put at 0 €/MWh. Cost of load shedding is fixed at 10 000 €/MWh.

For the storage technology a round-trip efficiency of 85% is chosen. Two cost scenarios are considered. In scenario *A* an energy cost of 50 €/kWh and a power cost of 1 000 €/kW are assumed. These costs are comparable to the costs of existing pumped hydro storage systems [17], [18]. In reality, many other storage technologies exist, with different technical and economic parameters. This technology is chosen as a representative form of storage. Furthermore, an expected life time of 20 years and a discount rate of 8% are assumed. In scenario *B* both the energy and the power cost are halved, meaning 25 €/kWh and 500 €/kW, while the expected life time and discount rate are kept constant.

The portfolio of the test system is optimized for a one year time period with an hourly resolution. Although possible, no initial installed capacities are assumed, meaning that e.g. the effect of the possible decommissioning of existing plants is not taken into account. Different minimum targets for the final renewable electricity use are imposed to study the influence hereof on the generation portfolio composition and uptake of storage. The target is increased from 0% to 50% with steps of 10%. The two storage scenarios – *A* and *B* – are then compared to a reference scenario *R* in which no storage is available.

III. RESULTS

A. *Installed generation capacity*

Figure 1 shows the installed generation capacity for the three different scenarios for the different RES targets. First, no *Base* capacity is installed in any of the scenarios as it appears to be too costly. Second, in the reference scenario the installed conventional generation capacity, after a slight initial decrease, increases as the RES target increases. At first, it decreases as the RES cover a part of the energy need. However, at higher RES targets this effect is countered by an increased need for flexibility. Thus, the installed *Mid* capacity decreases, while the installed *Peak* and *High Peak* capacity increase.

In the two storage scenarios the installed conventional generation capacity decreases. Furthermore, the conventional generation capacity mix is less flexible than in the reference scenario. As storage provides part of the required operational flexibility, the share of *Mid* capacity can be higher and the need for *Peak* and *High Peak* capacity is significantly reduced. Initially both these effects are rather modest, but as the RES target increases they are more outspoken. Scenario *B*, which sees increased storage investment (see Section III.B) due to the lower costs, exhibits a reinforced version of these effects.

In all three scenarios the installed renewable generation capacity logically increases as the RES target increases. However, this increase is smaller in the scenarios with storage. Again this is effect is more outspoken as the RES target increases, and again more so in scenario *B*. Storage allows for a more efficient use of the installed renewable capacity. This becomes evident when looking at the curtailed renewable output. At the 50% RES target in the reference scenario 17.8% of the RES output is curtailed (10.8% relative to total demand). In scenario *A* this decreases to 6.7% (3.6% relative to total demand). In scenario B this decreases further to just 3.8% (2.0% relative to total demand).

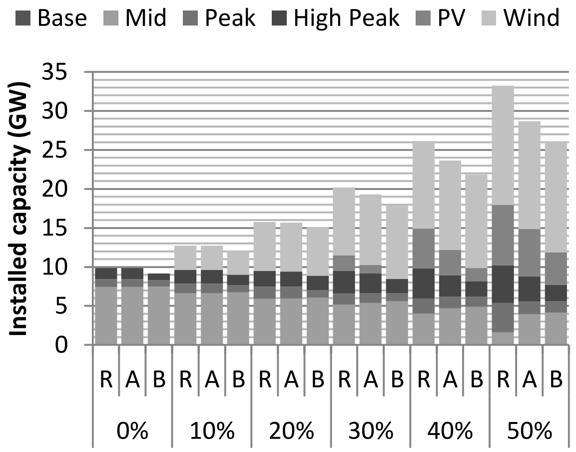

Figure 1. Installed capacities for the reference scenario *Ref* and the two storage scenarios *A* and *B*

Finally, the installed *PV* capacity is significantly lower than the installed *Wind* capacity. The reason for this can be found in the RES production profiles used here. The number of equivalent full load hours of the *PV* profile is approximately 1 000 hours, whereas it is approximately 3 000 hours for the *Wind* profile. At present, no limits are imposed for the maximum total installed RES capacities.

B. *Installed storage capacity*

The investment in storage strongly depends on both the target of variable RES and the assumed energy and power costs. Figure 2 shows the installed energy and power capacity.

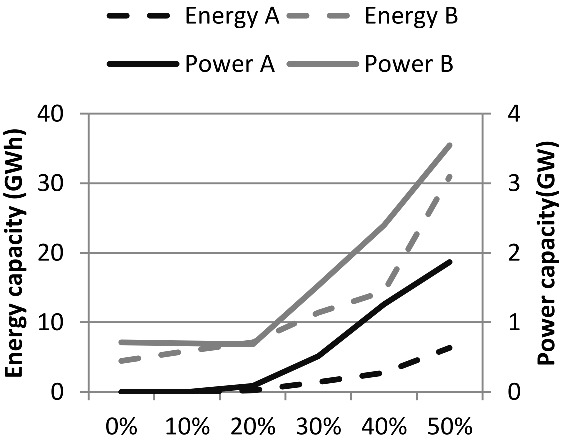

Figure 2. Installed storage energy and power capacities for the two storage scenarios *A* and *B*

The need for storage increases as the target for RES increases and the cost of storage reduces. In scenario *B* storage is sufficiently competitive to warrant investment, even in absence of RES, reducing the need for *High Peak* capacity. However, storage has most added value at high RES penetration. At the 50% RES target, storage provides more than 90% of the required aFRR, both upward and downward, in both scenarios. It also provides more than 80% of the required downward mFRR. In contrast, more than 90% of the upward mFRR is provided by conventional generation capacity, as this is more energy-intensive and would require reserving a significant share of the storage's energy capacity for discharging.

C. *Impact electricity generation cost*

The electricity generation cost is calculated by means of the ratio of the total system cost and the total energy demand, resulting in an average cost per MWh. For the reference scenario this cost evolves from 61.4 €/MWh at 0% RES to 87.0 €/MWh at 50% RES, an increase of 41.9%. For scenario *A* the cost evolves to 82.0 €/MWh at 50% RES, an increase of 33.7%, but a cost reduction of 5.8% compared to the reference scenario. In scenario *B* the cost at 0% RES drops to 61.1 €/MWh, a cost reduction of 0.4%. At 50% RES the cost is 79.4 €/MWh, an increase of 30.0%, but a cost reduction of 8.8% compared to the reference scenario. The potential for storage to reduce the electricity generation costs is found to increase as the RES target increases. Logically, this reduction is even larger as the storage costs come down.

IV. CONCLUSIONS

The availability of storage as an alternative source of operational flexibility has little impact in low RES scenarios. Considering current costs of storage, the needed operational flexibility can be supplied more economically by the conventional generation technologies. However, as the RES target increases, and with it the need for operational flexibility, storage has more added value. Both the installed conventional and renewable generation capacities decrease compared to the reference scenario. The electricity generation cost also decreases, by up to 5.8% at 50% RES for scenario *A* and up to 8.8% at 50% RES for scenario *B*. The potential cost savings brought on by storage will be even larger if other added values would be considered, such as the potential to deliver other grid services (e.g. maintaining voltage stability).

Future work needs to include a more in-depth analysis of the power and energy costs and of the charging and discharging behavior of different storage technologies. The potential of other alternative sources of flexibility, such as demand response or increased transmission interconnection, and their influence on the added value of storage will also be evaluated.

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