capacity should be required from the market whereas the cost of maintaining the capacity margin is subtracted from the objective function.

The LCP conditions based on equations (27) and (28) are formulated in equations (29) to (31).

$$\forall h: -\lambda_h * T + P^{MAX} * T \geq 0 \perp ls_h \geq 0 \tag{29}$$

$$\gamma - \beta \geq 0 \perp cap^{req} \geq 0 \tag{30}$$

$$cap^{req} - RS^{cap} * DEM^{MAX} \geq 0 \perp \beta \geq 0 \tag{31}$$

3.5. Energy Market

The LCP conditions for power producers, storage providers and the SO is coupled through markets, including energy and capacity. The energy only market (EO) balances the energy in the system for each time step of the operating period as shown in equation (32). The generation from power plants and storage added to the injected solar and wind production must at least be equal to the demand subtracted load curtailment. The energy balance is formulated as a >= restriction to account for situations with excess production due to the RES injection. If production is higher than the demand, RES curtailment will occur in reality.

$$\forall h: \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - charge_{s,h}) + INJ_h^{solar} + INJ_h^{wind} \geq DEM_h - ls_h \tag{32}$$

The energy price is calculated by applying the complementarity slackness theorem [20, p. 145] on equation (32) with λ as the dual variable as stated in equation (33).

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - charge_{s,h}) + INJ_h^{solar} + INJ_h^{wind} - DEM_h + ls_h \geq 0 \perp \lambda_h \geq 0 \quad (33)$$

3.6. Capacity Market

The modeled capacity mechanism is a volume-based capacity market similar to a simplified version of the auction in the Great Britain [26], [27]. The CM clearing condition can be found in equation (34) which states that the amount of generation capacity provided by conventional producers and storage units should be at least the capacity required by the system operator. The CM clearing will determine the lowest possible capacity price that will fulfill the balance. The capacity offered from storage units can be derated by applying a CF lower than one due to their energy limitations. RES capacity is not included in the CM.

$$\sum_{f=1}^{F} cap_f^{cm} + \sum_{s=1}^{S} cap_s^{cm} * CF_s - cap^{req} \geq 0 \quad (34)$$

Again, according to the complementarity slackness theorem [20, p. 145] the optimality condition of equation (34) is formulated in equation (35) with the capacity price, γ, as the dual variable.

$$\sum_{f=1}^{F} cap_f^{cm} + \sum_{s=1}^{S} cap_s^{cm} * CF_s - cap^{req} \geq 0 \perp \gamma \geq 0 \quad (35)$$

3.7. RES Generation

Generation from RES is represented by a time series of input data. The energy that is generated by wind and solar each period is a parameter and will not be affected by the rest of the model. The properties of different RES technologies and level of RES is not the scope of this paper.

If the RES production in the system exceed demand, there will be an overproduction. The assumption is that excess production is automatically curtailed as described in the energy balance in section 3.5.

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3.8. Regulator

The regulator controls the requirements for the SO. In the case of a capacity market the regulator requires a minimum percentage of the maximum demand, RS^{cap}, from the capacity market.

4. Case Study

The presented model is applied in a case study. The following underlying assumptions are made:

- The case study covers Belgium, France, Germany, and the Netherlands without any transmission constraints.
- Potential PHES is provided from Norway through a limited HVDC connection.
- Perfect market with no strategic players.
- The demand is firm and only affected by involuntary load curtailment.
- The scenario is deterministic.
- Power producers have a cost structure characterized by fixed and variable costs.
- Storage units have a cost structure characterized by fixed costs and losses.
- No ramping rate restrictions.
- RES production is characterized by a time series of injected power.

A case study on the given model is performed to assess the role of energy storage in the power system. Two different market designs are analyzed: EO and CM with a 100% capacity requirement. For each of the two market configurations, four different storage possibilities are analyzed, resulting into eight cases:

1. EO with no energy storage

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2. CM with no energy storage
3. EO with Norwegian PHES
4. CM with Norwegian PHES
5. EO with lead-acid batteries
6. CM with lead-acid batteries
7. EO with both storage technologies
8. CM with both storage technologies

Data for a full year were used to obtain robust results when comparing the short-term properties of batteries with seasonal operation of Norwegian pumped hydro energy storage (PHES). This poses a challenge concerning problem size. The operation pattern of batteries require a detailed resolution to capture short-term variations in prices whereas PHES requires a long time horizon to capture the seasonal variations. The analyses were performed with a 2-hour resolution. Computing time ranged from 5 minutes for the cases with no energy storage to approximately 4 hours for the cases with both storage technologies.

4.1. Input Data

4.1.1. Producers and storage

Input data for storage units and conventional power producers are presented in Tables 1 and 2. The calculations of annual fixed costs are based on a interest rate of 5% for all technologies. PHES is based on existing reservoir capacity in Norwegian hydropower and fixed cost for pumping and generation expansion including the HVDC interconnections to continental Europe. For the battery, cost parameters for lead-acid were chosen after performing initial analyses with lithium-ion battery data [28] which resulted in zero installed capacity due to high costs. In order to compare energy storage technologies with season-shifting properties (PHES) to a technology relying on short-term arbitrage, the lead-acid batteries provide a reference for assessing how the characteristics influence how the technologies operate in the market.

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Table 1: Technology characteristics for storage units [5] [18] [28]

	PHES	Battery
Fixed costs [EUR/MW]	114 098	25 901
Fixed costs [EUR/MWh]	0	6 475
Converter efficiency [%]	80	92
Self discharge [%/MWh]	0	0
Maximum Capacity [TWh]	15	-
Technology life [years]	30	10

Table 2: Technology characteristics for power producers [5] [29]

	Nuclear	Hard coal	CCGT	OCGT
Fixed costs [EUR/MW]	280 000	72 000	41 000	16 000
Variable costs [EUR/MWh]	3	35	48	150
Technology life [years]	40	40	40	40

4.1.2. Injected wind and solar power

The renewable energy injected into the system is a time series of hourly production injected into the system. Fixed costs for RES is problematic to predict. Hence, fixed levels of RES is chosen in the case study. The base data from the COSMO weather model gathered from [29] is scaled according to the ten-year network development plan by ENTSO-E [30]. Ignoring network restrictions, Belgium, France, Germany, and the Netherlands are modeled as one area. Based on Vision 4 the total RES share is 41.5% of total energy demand (30.5% wind and 11.0% solar) [30].

4.1.3. Demand

The source for demand data is the time-series data from ENTSO-E Vision 4 [30]. The data for Belgium, France, Germany, and the Netherlands are aggregated to represent the total demand for this area.

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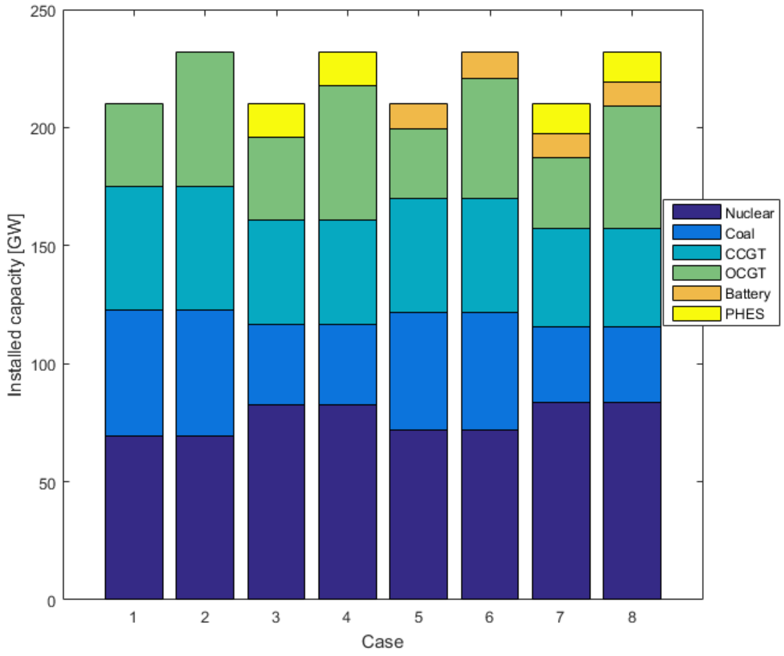

Figure 2: Installed Capacity

4.1.4. Regulatory restrictions

The regulator impose restrictions on the system operator. In the cases with a CRM the capacity margin, represented by RS^{cap}, is equal to 100% of the peak demand. The market price cap is set to 3000 EUR/MWh.

4.2. Results

4.2.1. Capacity

The equilibrium generation portfolio of all power producers and the energy storage units are shown in Fig 2. The according numbers are reported in Tables 3 and 4. Assessing the results, it is important to keep in mind that investments are purely determined by profitability. Derating of energy storage is not done in these initial results and is assessed further in section 4.2.2.

The studies show an increase in total capacity if a capacity market is im-

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plemented. The increase occurs as the capacity margin is set to ensure enough capacity for covering the peak demand and the capacity remuneration is determined by the capacity market to achieve the required capacity, satisfying a higher reliability standard than an energy only market with a price cap. The additional technology that is invested in, in order to fulfill the capacity requirement, is OCGT in the case of no storage available, as well as when only PHES is available. This is due to OCGT having the lowest fixed cost, whereas PHES is not competitive in the CM under these assumptions because it is not economical to invest in additional PHES to be used as stand-by capacity due to the high fixed costs. PHES serve as a long-term storage that require a high utilization rate because of the relatively high fixed costs compared to batteries and OCGT. However, when the battery is included in the market, a small increase in battery investments can be observed when comparing cases 5 and 7 (CM) to cases 6 and 8 (EO). This suggests that low-cost energy storage can be an economical alternative to peaking power plants. Further, in a real market setting, a capacity mechanism would lead to a more certain cash flow for the investments in such assets. The additional income stream from a possible capacity market is more reliable than relying on only arbitraging the energy market. Thus, the presence of a capacity market may be necessary to decrease the uncertainty of cost recovery for energy storage.

The capacity margin is designed to avoid any shortage of capacity in the system. However, situations with shortage of generation capacity are still possible with energy storage in the system due to the limited energy content. Hence, load curtailment would be the case in a situation with depleted storage and insufficient thermal generation capacity to cover the demand. In the analyses performed in this paper, no load shedding occurred with a CM. This may be explained by the deterministic approach since storage units will keep energy available for situations with generation capacity shortage since these are associated with very high energy prices.

The amount of OCGT capacity is decreased when a battery is included in the system. This suggests that the battery provides a cost effective alternative

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to OCGT for providing peaking power in the power system. Further, when both storage technologies are modeled simultaneously the results show that both are needed in the system, as the installed capacities of the energy storages are only slightly reduced compared to the single-storage cases. The storage technologies complements each other and further reduce the amount of thermal capacity instead of reducing each other's business opportunities. This will be elaborated further in section 4.2.2 and 4.2.3.

Table 3: EO Comparison of Results

	Case 1 No Storage	Case 3 PHES	Case 5 Battery	Case 7 Both
Nuclear [MW]	69 342	85 528	72 117	83 605
Utilization [%]	89.7	91.3	90.3	91.7
Coal [MW]	53 527	34 052	49 355	32 229
Utilization [%]	52.1	50.7	51.7	50.6
CCGT [MW]	52 291	44 405	48 707	41 566
Utilization [%]	11.6	9.50	11.4	9.36
OCGT [MW]	35 031	35 031	29 081	29 798
Utilization [%]	1.08	1.08	1.18	1.19
PHES [MW]	0	14 175	0	12 742
PHES [MWh]	0	15 000 000	0	15 000 000
Battery [MW]	0	0	10 930	10 251
Battery [MWh]	0	0	47 862	43 797
Load curt. [MWh]	26 533	26 533	26 533	26 533
RES curt. [MWh]	4 491 146	2 296 571	3 049 513	1 499 946

A large increase of 23.3% in nuclear generation capacity is observed in the cases with PHES (3 and 4) compared to the no storage cases (1 and 2). The nuclear power generation technology represent the base load unit requiring 6500 full load hours (FLH) to be cost competitive compared to coal. Energy storage, and especially PHES, is able to somewhat even out the residual demand in

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Table 4: CM Comparison of Results

	Case 2 No Storage	Case 4 PHES	Case 6 Battery	Case 8 Both
Nuclear [MW]	69 342	85 528	72 117	83 616
Utilization [%]	89.7	91.3	90.3	91.7
Coal [MW]	53 527	34 052	49 355	32 176
Utilization [%]	52.1	50.7	51.7	50.6
CCGT [MW]	52 291	44 405	48 707	41 610
Utilization [%]	11.6	9.50	11.4	9.36
OCGT [MW]	56 857	56 857	50 818	51 565
Utilization [%]	0.67	0.67	0.68	0.69
PHES [MW]	0	14 175	0	12 752
PHES [MWh]	0	15 000 000	0	15 000 000
Battery [MW]	0	0	11 018	10 297
Battery [MWh]	0	0	48 029	43 883
Load curt. [MWh]	0	0	0	0
RES curt. [MWh]	4 491 146	2 296 571	3 043 409	1 497 420

the system by storing excess energy when the prices are low and discharging when it is needed. Energy storage helps the base load capacity by storing excess low cost energy and dispatching it when the prices are higher. Hence, the base load capacity that can be run for the minimum FLH increases. The improved conditions for nuclear power give a substantial decrease of coal and CCGT generation capacity because some of the capacity can be replaced by a more cost effective mix of energy storage and base load nuclear power. OCGT capacity is not affected by including PHES in the system, but is decreased when batteries are introduced as previously explained.

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4.2.2. Sensitivity Analysis: Derating

Case 8, representing no derating (100% rating), is the base case for these analyses. Storage units have limited energy content. Hence, it is uncertain if these units can effectively generate when needed. Due to the disadvantages of storage units regarding fulfillment of the objectives of a capacity mechanism, derating of storage units may be warranted. The storage derating can be adjusted by changing the parameter CF_s which has been varied between zero (full derating) and one (no derating) in order to study different levels of derating of batteries in the capacity market. A storage unit with high risk of emptying the energy buffer would have a CF close to 0 whereas a unit with low risk of emptying would have a CF close to one. Compared to PHES, the battery has a relatively high capacity in relation to storage size, which means that it can easily deplete all the stored energy in a short amount of time whereas this is less likely for the PHES due to the large reservoir size.

The difference in capacity for a battery participating in a CM is shown in Fig. 3. It can be observed, that the installed generation capacity of energy storage in the case of CM is only similar to the case of EO if there is no derating, i.e. a CF_s close to one. This happens as the competitiveness of energy storage is drastically reduced when it does not receive the same remuneration from the CM as thermal generation units and PHES.

The relation between derating and installed capacity follows a linear pattern for the battery technology. There is no derating of PHES and the profitability of PHES is only slightly affected by derating of the battery, which means that PHES is not suited to fill the gap when battery capacity is reduced.

4.2.3. Sensitivity Analysis: Cost

Case 7, representing 0% cost change of batteries, is the base case for these analyses. Operational patterns of the battery such as increased cycling may give different cost profiles than the base case. The cost analysis is performed on the battery using the EO model by changing the fixed costs parameters. Both the storage size and capacity costs were changed by the same percentage value.

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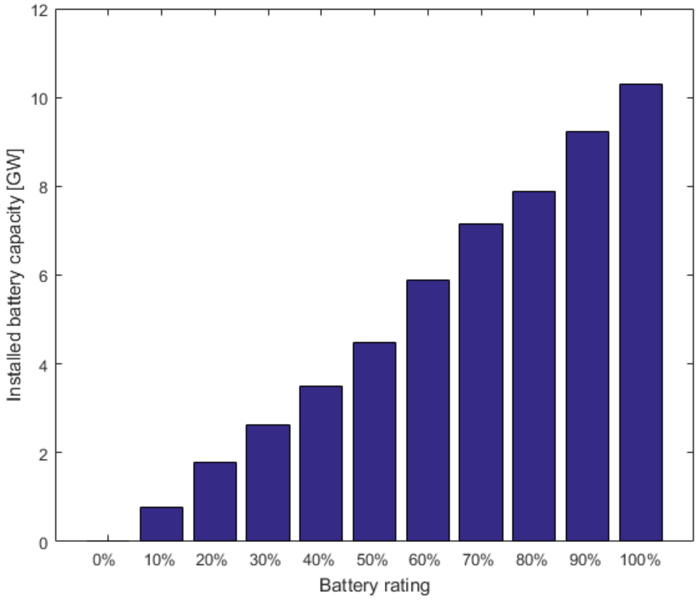

Figure 3: Battery sensitivity to derating in case 8

The costs were varied from -50% and increased in 10% intervals until the result was zero installed capacity. Cycling costs have not been modeled, but increased cycling would mean increased battery cost. Hence, this section provides some insight to how this would affect the outcome.

Fig. 4 show the results for a battery in the EO model. Similarly to the previous section, the installed capacity relation to costs follow a linear pattern. A 30% cost increase resulted in zero installed capacity. These results indicate that although the battery investment decision is sensitive to costs, the result will not be very different for relatively small changes. Further, the profitability of lead-acid batteries show that if the cost of lithium-ion batteries can be reduced to a level approaching the level of lead-acid batteries it should be possible to profitably operate these without subsidies.

PHES costs were kept constant throughout these analyses and the change in battery costs did not have a significant on the installed PHES capacity. PHES

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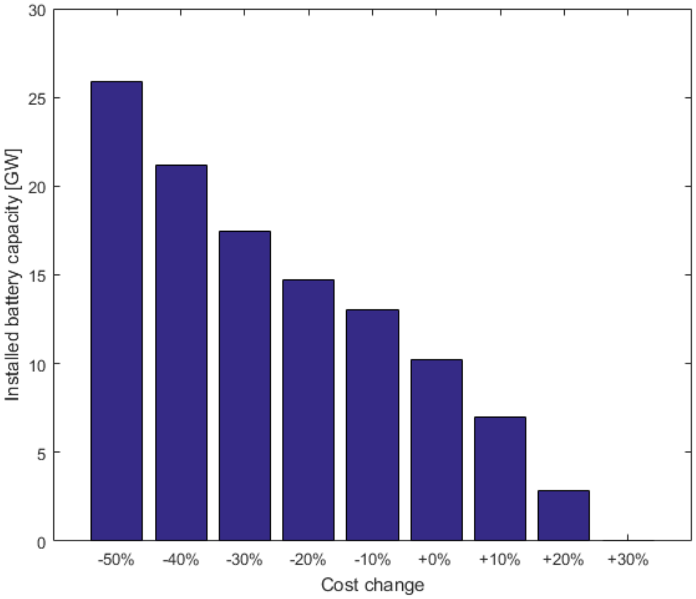

Figure 4: Battery sensitivity to costs in case 7

capacity ranged from 10 426 MW when the battery cost were half of the base case costs to 14 175 MW with battery costs at +30% relative to the base case. Similar to previous results, these findings indicate that PHES and batteries complements each other rather than compete.

5. Conclusion

A complementarity model of a power system is developed to assess the potential of energy storage under energy only and volume-based capacity market conditions in a scenario with a renewable energy source share of 41.5% of total demand. Norwegian pumped hydro energy storage and lead-acid batteries have been analyzed in order to compare results for technologies with different characteristics.

It is found that batteries can be a cost effective alternative to peaking power thermal generation (OCGT) for covering some of the peak load and contribute

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to a capacity reserve requirement if a capacity market is implemented. The competitiveness is a result of the cost structure of the battery and the high efficiency, resulting in a relatively high capacity in relation to storage size.

The introduction of Norwegian pumped hydro energy storage in the system resulted in an increase of 23.3% of nuclear power, the base load unit. This is because the pumped hydro storage is able to shift load so that the residual demand becomes more even, giving increased competitiveness for nuclear power compared to coal.

Derating of the batteries were discussed and a sensitivity analysis show that if a capacity market is implemented, possible storage derating is important for the competitiveness of batteries since it creates a bias against batteries. Batteries were able to provide a cost effective alternative to OCGT for providing some of the peaking power.

The two storage technologies considered in this paper have different roles in the system and complements each other rather than reduce each other's business opportunities. The findings suggests that there is no universal energy storage technology. Several options need to be implemented in the same system to reap all the benefits that are possible from introducing storage units as a tool to balance the power system.

The presented model provides a starting point for further research. For example, reserve markets are not included in this paper and is one of several future development possibilities. Additional topics of further work are increased detail for the battery model, additional markets, increased detail for thermal units, and investments in renewable energy sources.

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