HYDRAULIC STORAGE DEMAND FOR A FULL REGENERATIVE ELECTRICITY POWER SUPPLY OF AUSTRIA

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Abstract: In this paper, the necessary additional hydraulic storage demand (capacity and power) is determined, that would be necessary for a full supply of Austria with electricity from renewable sources, i.e. hydropower, wind power and photovoltaics. Therefore a multi-level optimization of the generation mix has been implemented. The results show that the necessary storage demand exceeds the existing hydraulic storage potential in Austria, in some scenarios by orders of magnitude.

1 Introduction

The worldwide demand for electricity continues to rise. Responsible for this are various factors such as the industrialization of emerging countries, but also the substitution of other energy sources in industrialized countries. To meet this growing demand also power plants that use fossil primary energy sources are used. Due to the finite nature, coupled with sometimes unstable political situations in the supplier countries the price increases. Many countries (including Austria) are depending on imports of fossil fuels, so the situation is even worse. And finally the climate change is aggravated by greenhouse gas emissions from fossil-fueled plants.

For the above reasons a modified structure in the field of electrical energy supply is needed. Electricity from renewable sources such as hydroelectric power, wind power or photovoltaics will increasingly replace electricity from fossil power plants.

However, the renewable sources bring in addition to their many advantages (free primary energy, decrease in greenhouse gas emissions, decreasing import dependency for other energy sources, decoupling of rising energy prices, etc.) also some disadvantages. The high volatility caused by the nature of wind or solar radiation is a significant problem. Flexible backup units must be available to compensate these fluctuations to provide a stable network operation. Furthermore, the local potential for renewable energy is distributed inhomogeneously. In addition, generation systems such as wind power and photovoltaic are also characterized by very low full-load hours, which makes it necessary to install much higher capacity than, for example, hydropower or thermal units in order to achieve equal amounts of energy. On the one hand this loads the power grid, as higher transmission capacities are required. On the other hand, the role of storage in a sustainable electricity system is becoming increasingly important, as they have to manage the balance between volatile, renewable producers and flexible consumers.

The central question of the research project “Super-4-Micro-Grid – Sustainable energy supply and climate change” [1] was if a full supply of electrical energy in Austria is possible based on the national potentials for hydro power, wind power and photovoltaics. As the question could be answered in the affirmative [2], the question on the needs of storage capacities for such a system arose. This question should be answered in this paper. To determine the minimum storage requirements a multi-level optimization has been implemented and the results are compared with the hydraulic storage potentials for Austria. Further analysis of the impact on the transmission system [5] and the necessary storage demand were performed.

2 Methods

This chapter reports on the fundamental assumptions and limitations to the data base used. Thereafter, the scenarios are shown, which were developed for further considerations. Finally, the implemented multi-level optimization to minimize the storage demand will be discussed.

2.1 Assumptions

In the project it was assumed to regard Austria as an island system. This implies the independency of this system in two stages: First, the energy autonomy, and second, power self-sufficiency. The latter condition outperforms the first and requires the balance of production and consumption of electricity at all times to provide a stable network operation. As compensatory component in the considered power system storages can be used, whose scale is to be determined.
As a further assumption, only renewable sources, i.e. hydropower, wind power and photovoltaics are considered. Other renewable sources like biomass are excluded in the modelling. For run-of-river power stations the assumption was made that no lockers are available, so the production is equal to hydraulic supply.

2.2 Data base

The approach is based on time series for hydroelectric power, wind power, photovoltaics and load in a temporal resolution of one hour over a period of 15 years (1994 to 2008). The renewable power feed-in was all modelled on basis of meteorological data of wind speed, solar radiation and the precipitation. In parallel, using a Geographic Information System (GIS), the national potentials for wind and solar power were investigated [1], [3]. For this purpose Austria was divided into eight homogeneous regions, taking into account climatological characteristics.
Based on research, existing as well as future planned (pump) storage plants in Austria were investigated, with their characteristic parameters. [4]
For load modelling data from e-Control for 2007 and 2008 were used. The whole load of Austria was broken down based on geographic and demographic data on eight regional loads. This information is also in an hourly resolution.

2.3 Scenarios

Since the projections of future trends, such as the development of electrical energy consumption in Austria, are associated with very large uncertainties six scenarios were developed. As variable, on the one hand the annual production potential from hydropower was selected, and on other hand the development of the electricity demand. The following values for the two parameters were determined:

- **Hydro power**: 41 TWh/yr ("basis") and 51 TWh/yr ("expansion")
- **Electricity demand**: 69 TWh/yr ("Low"), 86 TWh/yr ("Medium) and 137 TWh/yr ("High")

The six developed scenarios are shown in Table 1.

		Annual electricity demand 69 TWh ("low")	86 TWh ("medium")	137 TWh ("high")
Annual hydropower generation	41 TWh ("basis")	Scenario LB	Scenario MB	Scenario HB
	51 TWh ("expansion")	Scenario LE	Scenario ME	Scenario HE

Table 1. Scenarios of annual hydropower generation and annual electricity demand for Austria until 2050

The colour markings of the scenarios have the following meanings:
- **White**: The investigated national renewable power potentials are sufficient to meet the energy demand needs.
- **Light grey**: The investigated national renewable power potentials have to be scaled up by a factor 1.5 to facilitate the energy demand needs.
- **Dark grey**: The investigated national renewable power potentials have to be scaled up by a factor 4.3 to facilitate the energy demand needs.

The scenario ME is used as the reference scenario. It assumes a consumption growth of 25% and an increase in hydropower generation to around 51 TWh per year by 2050. The energetic coverage of the electrical load with the identified potential is possible.

2.4 Storage optimization

This section is the central element of this paper. It explains the multi-stage optimization of the energy mix for minimum storage requirements. In a first step the optimization targets are presented, as well as the constraints. After that the multi-stage process is presented, which also contains the optimal processing of the standard capacity of storage hydropower plants.

2.4.1 Objective function, constraints and variables

As an objective function optionally the storage capacity (energy content) or the pumping capacity (pump power) of the required storage can be minimized. For labelling the target that has been selected the suffixes "-1" for the minimum storage

capacity, or "-2" for the minimum pump power are added to the scenarios names (e.g. MB-1, LE-2, etc.).
As a constraint the power consumption including losses due to loading and unloading the storage must be met by renewable generation over the observation period of 15 years. The production shares of wind and solar power must not exceed the calculated potential in the eight regions. The corresponding minimum value of production shares of these two technologies in each region is zero.
To perform an optimization, one or more variables are required that can be varied within certain limitations. In the present case, these are the shares of wind power and photovoltaics in the eight regions defined. The optimal generation mix is accordingly that mix of the regional wind and photovoltaic power supplies, which minimizes the selected objective function.

2.4.2 Implementation

The optimization was implemented in MATLAB. The Solver *fmincon* and the *active-set* algorithm were chosen from the supplied *Optimization Toolbox*. Due to the complexity of the problem, a multi-start problem has been formulated in order to find the global and not a local minimum with different starting values.
The scheme of the multi-level optimization process is shown Fig. 1 in. It is an iterative process. The individual process steps are explained in detail below.

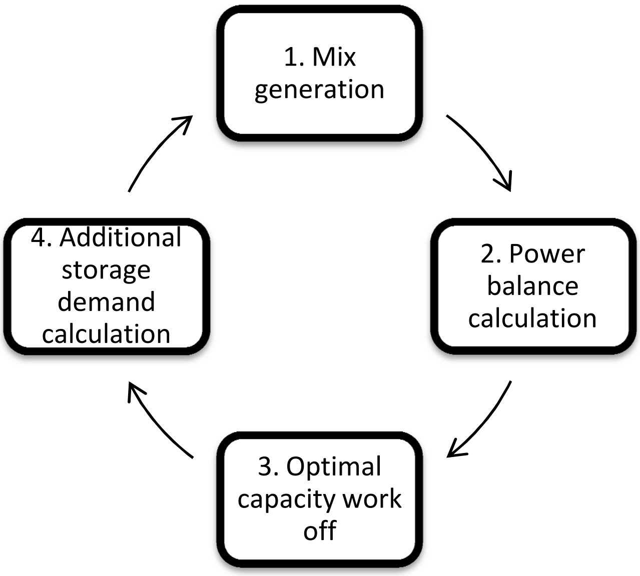

Fig. 1. Scheme of multi-stage optimization

1. At the beginning of the optimization, a start-generation mix is chosen, i.e. assumed weights for the eight regional wind power units and the eight regional photovoltaic components between zero and their potential limits. Thus, the assumed composition of generation from wind power and photovoltaics for the first iteration of optimization is fixed. The time series of hydropower generation have already been determined by the choice of scenario, because it is always used in full and is not variable.

   The supply is calculated for every timestamp t out of 131’496,

$$\text{supply(t)} = \sum_r \sum_T MixShare_{r,T} * ValueSeries_{r,T}(t)$$
$$\text{Regions } r \in \{1, \dots, 8\}$$
$$Technologies\ T \in \{run\ of\ river, wind\ power, photovoltaics\}$$
$$MixShare \in \{0, \dots, bound\ of\ regional\ potential\}$$
$$Timestamps\ \text{t} \in \{1, \dots, 131'496\}$$

2. In the second process step the demand is subtracted from the supply for every timestamp,

$$power\ balance(t) = supply(t) - demand(t)$$

3. Based on this power balance the work off of the standard capacity of the hydro storage power plants is optimized in the third process step. The optimization is divided into daily, weekly and yearly stages. The scheme of this process is shown in Fig. 2.

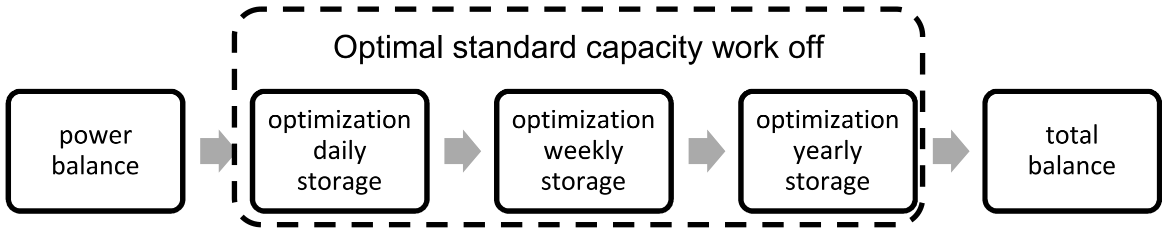

Fig. 2. Scheme of storage optimization by stages

The aim of this optimization is that the available standard capacity of hydro storages is optimally used, i.e. to absorb large production deficits. An additional constraint for the storage use is the maximum capacity of the turbines. The standard capacity is evenly distributed over these periods. As an example the performance characteristics of the original power balance, and the curves at the end of the day, the week, and the annual storage optimization for the period of a week is shown in Fig. 3. With each stage of the optimization the profile is further smoothed. The rest of the power requirement was reduced from around 6.5 GW to about 2 GW. As results for this optimization level you get the total balance,

$$total\ balance(t) = power\ balance(t) - optimal\ capacity\ work\ off(t)$$

The maximum hourly value of the total balance is the highest required pump power, the minimum hourly value (negative) the highest required turbine power.

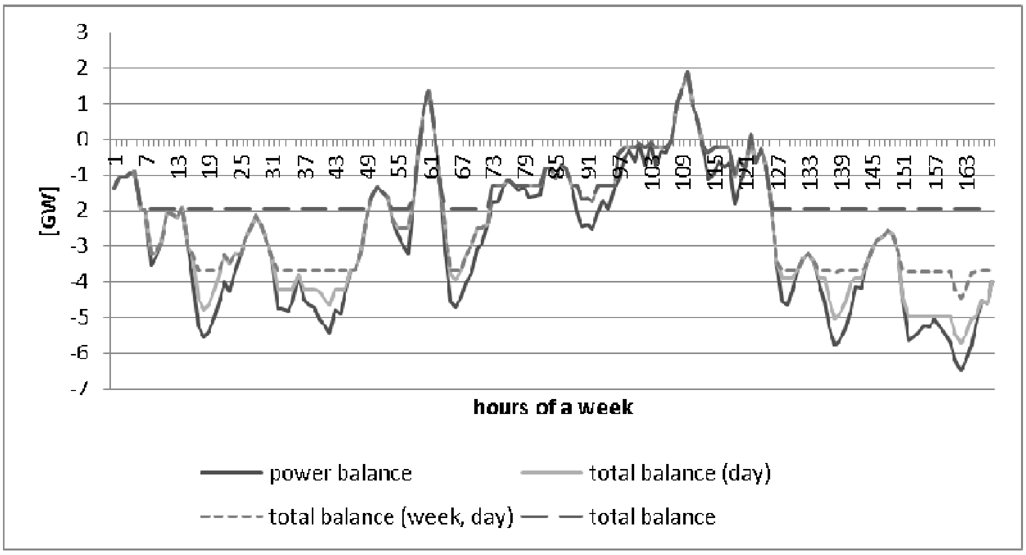

Fig. 3. Power characteristics of the original power balance and after the three levels of optimization

4. In the fourth and final step of the iterative optimization process the necessary additional storage capacity is determined. It is assumed that the additional storage capacity is provided in the form of pumped storage power stations. The system efficiency of pumped storage (assumed to be 80%) is, for reasons of simplification, split into two equal efficiencies for pumping or turbining,

$$\eta_{pump} = \eta_{turbine} = 89.44\%$$

Thus, the loading and unloading of the storage can be calculated on hourly basis,

$$balance(t) = total\ balance(t) - |total\ balance(t)| * \left(1 - \eta_{pump}\right)$$
$$\forall t \mid total\ balance > 0$$

$$balance(t) = total\ balance(t) - |total\ balance(t)| * (1 - \eta_{turbine})$$
$$\forall t \mid total\ balance < 0$$

By adding up, shifting the minimum storage content to zero and searching for the maximum value the additional required storage capacity can be calculated.

$$storage\ capacity = \max\left(\sum_t balance(t) - \min\left(\sum_t balance(t)\right)\right)$$

The required storage capacity is an indicator of the quality of the chosen generation mix. The optimization process then varies the generation mix, in order to find the optimal mix. If the storage requirement between two passes will not change significantly, the optimization is terminated.

3 Results

In this chapter the main results for the two selectable objective functions minimum storage capacity ("-1") and minimum pumping capacity ("-2") are presented and discussed for different scenarios.
For the six scenarios defined the calculated compositions of the supply mixes for the minimum storage capacity optimization goal are compared in Fig. 4. The shaded areas (MB-1, HB-1 und HE-1) indicate that a rise in the renewable energy potential is required to cover the load including losses (see section 2.3).
Within the scenarios three stages for the demand development were defined, which are now reflected in three pairs of columns with similar levels. Minimal differences within the pairs exist due to different losses. The shares of hydropower generation will vary depending on the scenario between the two stages of 31 TWh/yr and 41 TWh/yr. The standard capacity of storage power plants is always constant at around 10 TWh/yr.

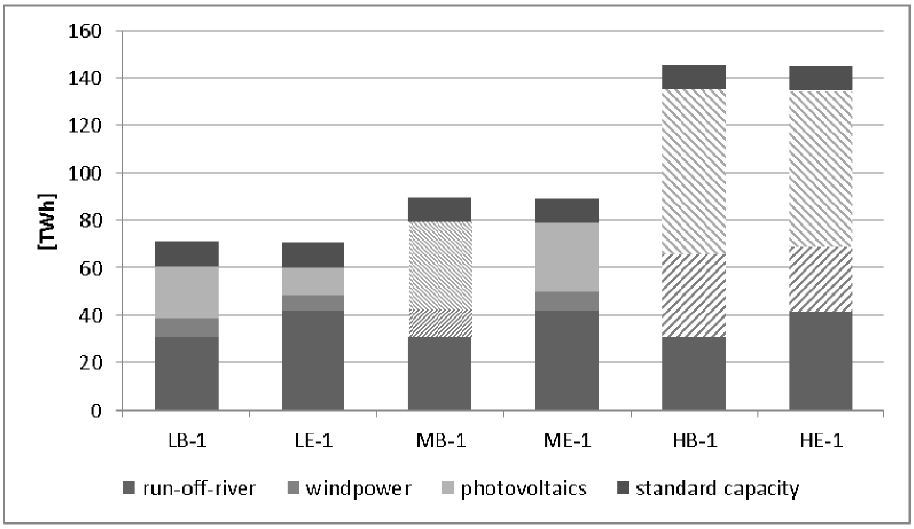

Fig. 4. Composition of production technologies to meet the demand including losses for different scenarios in TWh; shaded areas represent potential overruns

Between the scenarios there are also significant differences in addition to the stated similarities. In comparison with the reference scenario ME (shown in detail in Fig. 5) the following facts can be seen:

- If the amount of hydroelectric generation is not expanded at the same consumption, then the shares of photovoltaic and wind power have to be increased beyond their potential limits to cover the energetic demand, even if the consumption remains at the same level (scenario MB).

- If the power consumption can be held at the level of 2008 (68 TWh/yr) and the hydropower expansion is enforced (scenario LE), then the necessary shares of photovoltaic and wind power can be reduced to a total of around 20 TWh/yr. The average annual photovoltaic supply is thereby reduced significantly from around 29 TWh/yr to about 13 TWh/yr. The wind component is reduced only slightly.

- Only if the load is maintained at the level of 2008, it is possible to cover the demand without expanding hydroelectric generation and simultaneously not exceeding the potentials for wind power and photovoltaic (scenario LB).

- If the consumption doubles from 2008 to 2050 (this corresponds to an annual increase of around 1.66%/yr, scenarios HB and HE), then the coverage of the demand is only possible with massive exceeding of the potentials for wind power and photovoltaic even if the hydropower generation is expanded. The solar share of the annual electricity generation in the two scenarios would be around 50% that of wind power at 20-25%.

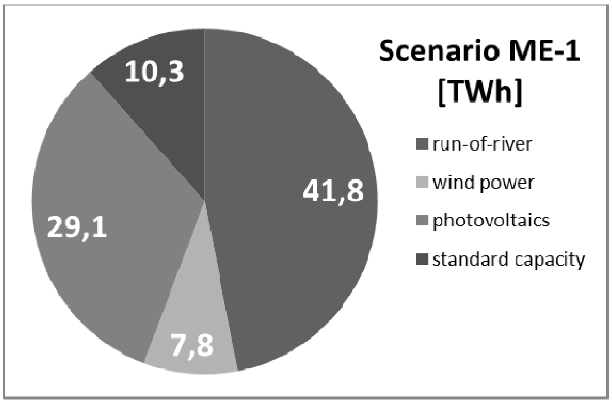

Fig. 5. Generation composition for load coverage for the scenario ME-1 in TWh

Fig. 6 shows the annual profiles of the storage level of the additional storages needed for the 15-year observation period. The annual courses were each displaced horizontally so that it has a minimum value of zero. Qualitatively, the trend is similar to today's hydraulic storages with natural inflow. The storage is empty after the winter (March, April), filled over the summer and peaked at September to October. The 15 years presented here have maximum values between 10 TWh and 14 TWh.

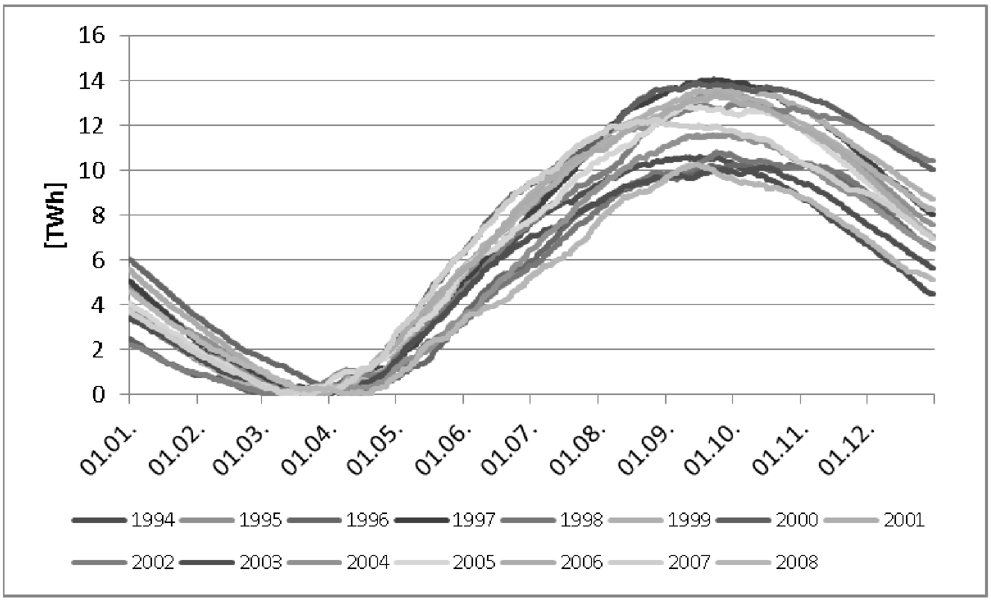

Fig. 6. Storage level at annual consideration for the scenario ME-1 in TWh

If these annual courses are attached to each other and the overall course is again shifted so that the minimum level is zero, the overall course is obtained shown in Fig. 7 (black solid line). Moreover, the levels at the beginning of years (grey squares) and the annual level changes (grey dashed line) are shown. Due to the constraint of the optimization that the energy recovery of the load and losses may be given over the observation period, the start corresponds to the final value. The maximum of the curve is at 23.4 TWh. This storage capacity would have to be held to allow the balanced accounting over the period of several years. It turns out that several years of considerations would be necessary to map the impact of a full supply by renewable electricity. As the figure indicates, during years with high renewable yield reserve has to be built for other years with less renewable production to maintain the energy balance over years.

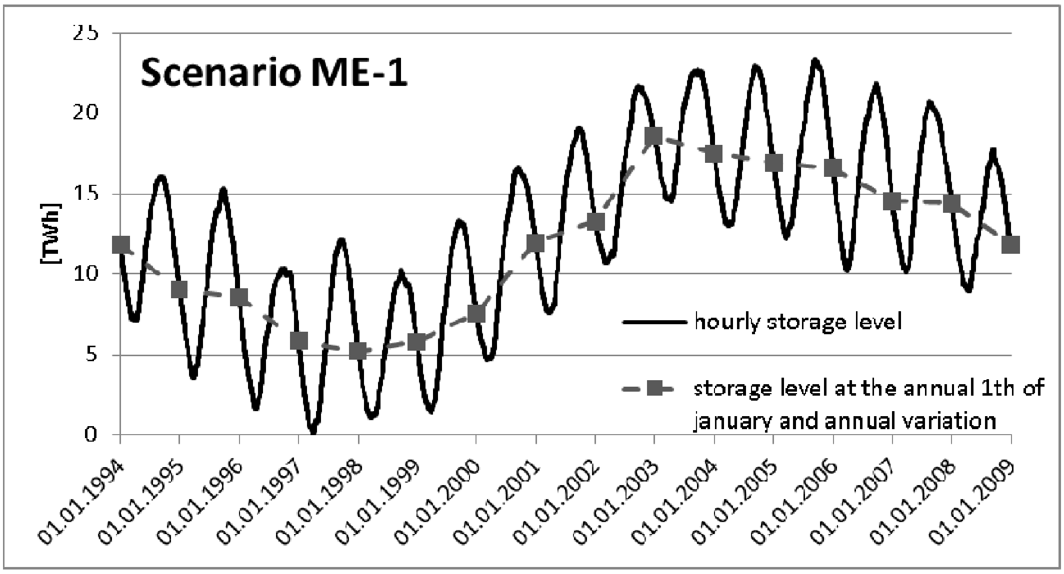

Fig. 7. Storage level of additionally required storage capacity over the observation period of 15 years and by the annual 1th of January as well as the annual variation for scenario ME-1

In addition to the necessary storage capacity the maximum required pump powers for the interim storing of energy were also determined. A comparison of these is shown in Fig. 8. The values range from about 12 GW (scenario LZ) and around 56 GW (scenario HB). Again three pairs with similar order of magnitude of the maximum pumping capacity can be seen. The differences within the couples but also between the scenarios are due to the fact that with increasing amounts of wind and solar shares more sites with lower quality (low full-load hours) must be used. This leads to increasing installed capacity to be able to deliver the same amount of energy. If, however, the rare event occurs that many renewable generation systems feed into the electricity grid simultaneously, the massive surpluses must be stored.

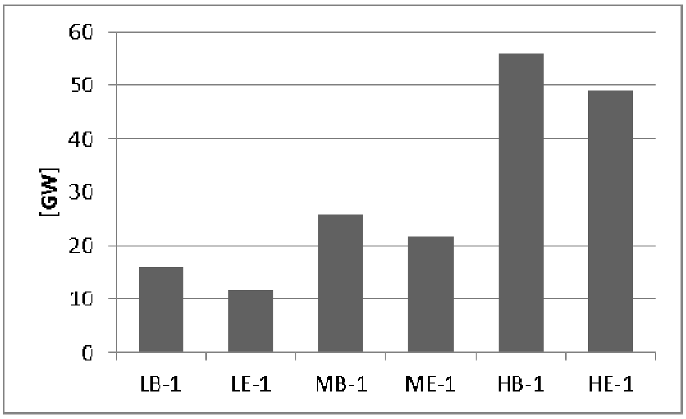

Fig. 8. Maximum pump power for different scenarios in GW

The fact that these relationships actually occur rarely, is given in Fig. 9. There the annual duration curves of the storage services are shown for the different scenarios (positive: pumping power, negative: turbine power). It can be seen on the right hand side of the image that very high pump powers are only necessary a very few hours per year. For example, consider the best-case scenario LZ. The maximum pump power can be reduced by one third (from 11.7 GW to 7.8 GW) just if the 48 hours with highest services would be limited.

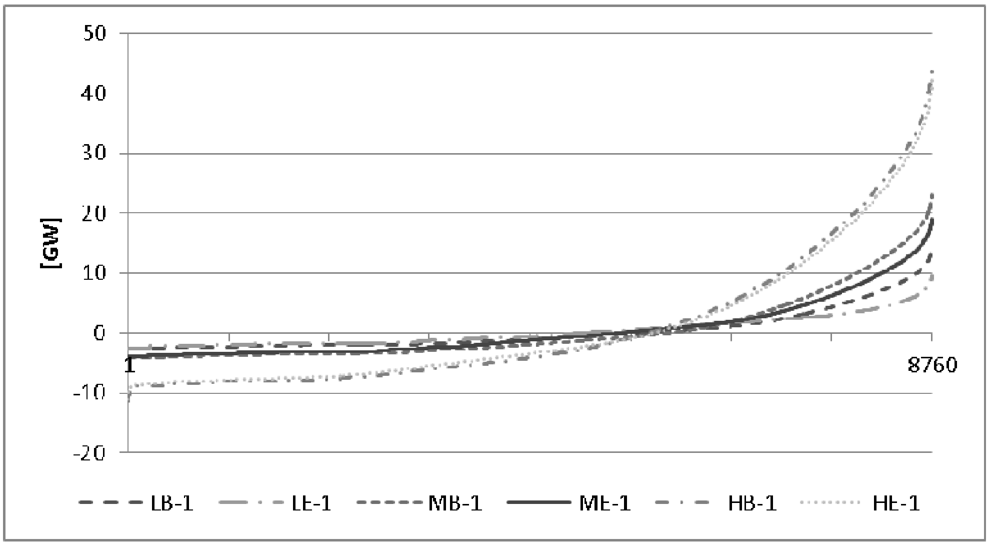

Fig. 9. Annual duration lines of storage power for various scenarios in GW

4 Summary and recommendation

By optimization of the generation mix from wind power and photovoltaics, combined with the generation of hydroelectric power and the optimized processing of the standard capacity in storage plants, the minimum necessary storage and pumping capacities for a regenerative power full supply for Austria for different scenarios have been identified.

Table 2 shows the required storage capacity and maximum pump powers for selected scenarios and optimization objectives against the Austrian potentials. The need for pumping capacity exceeds the potential depending on the scenario by a factor of two to four. The necessary storage capacities exceed the potentially available capacity by more than a factor of 100.

	Storage capacity [TWh]	Max. pump power [GW]
Austria's potential	0.14	4.8
Scenario LZ-1	17.0	11.7
Scenario LZ-2	17.3	10.6
Scenario MZ-1	23.4	21.4

Table 2. Required storage capacity and maximum pump performance under selected scenarios compared with the Austrian hydro storage potential

It could also be shown that for a full supply of Austria with electricity from renewable sources, hydropower, wind power and photovoltaics, the need for a multi-year storage management would be necessary (Fig. 7). In years with high renewable supply provisions must be made for poorer production years.
As a key factor towards a full renewable electricity supply the electricity consumption was identified. The lower the consumption, the lower the proportions of volatile generation technologies such as wind and solar power, and the lower the necessary extension services for sustainable production systems, as poor locations can be avoided. Moreover, it was also shown that the expansion of hydroelectric power would have considerable benefits.
In summary, the study pointed out that there would be sufficient regenerative potential in Austria to perform an autonomous full supply of electrical energy, but especially the additional required storage capacity exceeds the national potential massively.

Acknowledgement

The project “Super-4-Micro-Grid” was supported by funds from the “Klima- und Energiefonds” and performed within the program “NEUE ENERGIE 2020”.

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