EUSALP EU STRATEGY FOR THE ALPINE REGION

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Energy storage in the EUSALP region

Review of options for a safe and sustainable development

80 million people, 7 countries, 48 regions, mountains and plains addressing together common challenges and opportunities

Interreg Alpine Space AlpGov

EUROPEAN UNION

The project is co-financed by the European Regional Development Fund.

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This publication is a report by the EUSALP Action Group 9. It aims to provide evidence-based scientific support to the European policymaking process. The scientific output expressed does not imply a policy position of the members of the EUSALP Action Group 9 members.

This publication was realized in the frame of the Alpine Space project "Implementing Alpine Governance Mechanisms of the European Strategy for the Alpine region" (AlpGov). This project is co-financed by the European regional Development Fund through the Interreg Alpine Space programme.

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INTRODUCTORY NOTE

Making energy supply more sustainable and renewable is an agreed policy goal of the European Union. With the energy transition, we are facing new challenges to operate a stable energy system. This led us to the question of how the energy system in the Alps may look like in the future. In addition to the large hydropower plants, smaller and decentralized pants will increasingly be characterized by the expansion of renewable energy in the Alpine region. The volatility of solar and wind power, as well as a continuous expansion of e-mobility, will be challenges for the storage capacities and grid infrastructure of an increasingly decentralized and complex energy system. At the same time, this also reveals new opportunities: innovation and new business models emerge, consumers become “prosumers” and citizens’ participation models will give the energy transition a push.

Due to its central position in Europe and its topographic characteristics that have favoured hydropower installations for energy supply over the last decades, the Alps became also known as “Europe’s water tower”. It will be crucial to answer the question, which role energy storage infrastructures will play in the Alpine energy transition to cushion energy market fluctuations resulting from the increase of photovoltaic and wind energy expansion. The European energy transition is built on the decarbonisation through sustainable electrification of the housing (to cover heating and cooling needs) and the transport sector. By 2050, Europe’s electricity sector needs to be produced almost carbon free to reach set energy and climate targets. At the same time, the availability of natural water resources may in some parts of the Alps be affected by climate change phenomena.

A renewable and resilient energy system in the Alps will therefore need to provide a reliable energy storage system able to respond to volatility of electricity generation from renewables. The present report intends to contribute to the discussions about the role of energy storage in the Alpine energy transition built on a variety of possible scenarios of the energy Alpine-wide energy mix.

Ulrich Santa and Maren Meyer, EUSALP Action Group 9 co-leader, Energy Agency South Tyrol-CasaClima.

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SUMMARY

European legislation promotes the use of renewable energy through the Renewable Energy Directive and other documents. Until the year 2050, at least 80 % renewable energy sources in electricity will be used. The intermittent nature of renewable energy sources availability will impose new requirements to the electric energy system, among them a requirement for more energy storage.

Among renewable sources, photovoltaics (PV) features a distinctive daily and yearly pattern of generation. Average daily pattern of generation is shown in Figure 1. Here, as an example, demand in the EUSALP territory and average PV generation are shown according to current installed power (PV) and PV availability measured for the EUSALP region for middle of June. Current installed PV generation is unable to cover entire electric energy demand. Increase in PV (10 x PV and 30 x PV of currently installed PV capacity) can generate much more electric energy, however there is a lot of surplus generation during the day, which can't be used. Three times increase of installed power from 10 x PV to 30 x PV, both unreasonably high, can only additionally cover requirements in electric energy demand during four hours of the day, as shown with red arrows in Figure 1. PV generation alone is unable to provide all energy requirements, regardless of its installed capacity. Wind power plants on the other hand, have a more favourable daily pattern of electric energy generation.

Any future scenario of high renewable energy sources in electric energy generation will include energy storage. Within this report, we will review properties of individual energy storage methods and their suitability for the EUSALP region. To show requirements of the EUSALP region, we have developed a model, where electric energy generation and consumption are modelled in hourly intervals such that generation equals consumption and storage. Renewable energy sources and energy storage installed power are included in the model. Their installed power can be modified to set selected % of renewable energy. Amount of surplus energy (energy, which cannot be used or stored), for the entire year is estimated. Results of modelling show, that scenarios with high PV share in renewable energy generation produce very high amount of surplus energy, up to 600 TWh per year for the entire EUSALP region and 80 % renewable energy sources in electricity. Required installed power for PV and wind power plants for such scenario is also excessive, up to 16 x of today's installed power. High surplus energy and high-required installed power make PV a very unattractive source of electric energy for current and future investors.

Energy storage improves utilisation of renewable electric energy sources. With well-developed energy storage no electric energy will be surplus, while required installed power of renewable energy sources in the EUSALP will decrease by almost 50 % for comparable scenario with the current amount of electric energy storage.

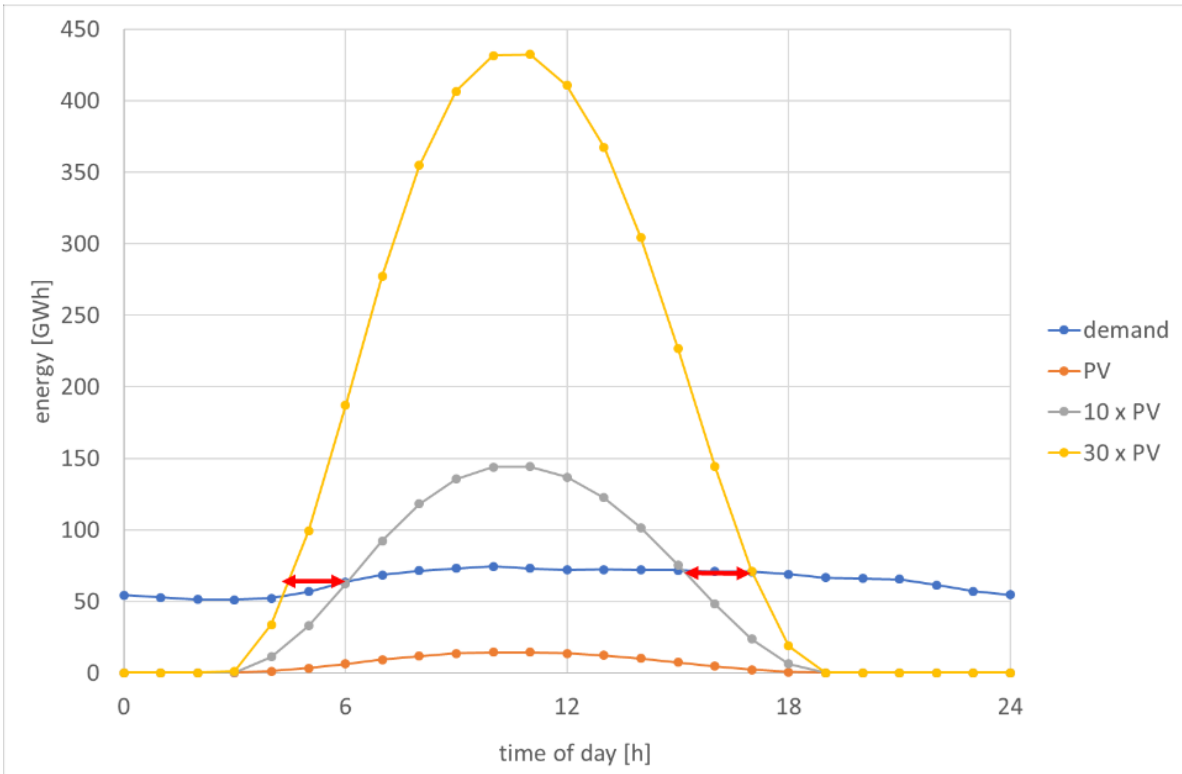

Figure 1: Hourly electric energy demand and photovoltaics production for the EUSALP region on average 15th of June. Any increase of installed PV power cannot provide enough electricity to cover demand without electric energy storage. The increase of installed PV power from 10 x of 2016 value to 30 x of 2016 value can cover less than 2 hours intervals in the morning and in the afternoon (shown with red arrow).

SWOT analysis has shown that pump storage hydro is the best energy storage option for the EUSALP region. Among pump storage hydro advantages are very favourable geographical conditions, possibility to sell/buy stored energy outside EUSALP region, possibility to store a very high amount of energy without seasonal variability and very long lifetime of pump storage hydro installations because of fully developed and reliable technology. Based on this, pump storage hydro offers cheap operation and predictable oper-

ation and maintenance costs. In addition, pump storage hydro technology is locally available from companies within the EUSALP region, enabling further possibility to sell knowledge, services and equipment worldwide.

As discussed for Figure 1, high renewable electricity scenarios will introduce high requirement for electric energy storage. Results of modelling show, that for the EUSALP region alone, this may reach up to 10 times of today's installed pump storage hydro power. Considering the favourable EUSALP central European position, the service of electric energy storage may be sold to neighbouring regions with less favourable conditions, increasing EUSALP electric energy storage requirements even further. For the reason of high storage requirement and to provide self-sufficient electric energy storage on local level, small pump storage hydro should be installed in the EUSALP region. Small pump storage hydro installation will be well implemented in smart grids, bringing together producers, users and storage of electric energy on local level, for instance through smart grids and peer to peer trading.

Disadvantages of pump storage hydro power plants are few. Most of them are related to investment costs, site planning and limited involvement of local communities. To promote electric energy storage and provide stable electric energy supply, EUSALP regions must provide for legislation, much reducing complexity and duration of pre-investment period, while investors must work together with local communities for better public acceptance of pump storage hydro power plants.

Among other electric energy storage technologies electrochemical energy storage will be useful for short and high frequency fluctuations of electric energy production and demand. The total amount of stored electric energy in electrochemical battery storage will however remain low due to inherent limitations of current technology.

LIST OF ABBREVIATIONS

The following abbreviations were used in the report:

EU - European Union

EUSALP - EU-Strategy for the Alpine Region

EV - electric vehicles

GRAND - global reservoir and dam database

HPP - hydro power plants

HVAC - heating, ventilation and air conditioning

ICOLD - international commission on large dams

M&O - management and operations

PSH - pumped storage hydro

PSR - pump storage requirement

PV - photovoltaics

RES - renewable energy sources

SWOT - strengths, weaknesses, opportunities and threats analysis

1. INTRODUCTION

The report will review various electric energy storage options and provide a model for calculation of requirement for electric energy storage. In this introductory section, we will discuss the development of the electric power system up to year 2050 and the transition to 80 % renewable energy sources in electric energy in relation to requirements of energy storage. In the second section, the pump storage requirement model methodology will be presented, while results will be shown in section 3. In section 4, a SWOT (strengths, weaknesses, opportunities and threats) analysis of various storage options will be provided, while in the last section 5 the most suitable electric energy storage option being pump storage hydro will be discussed together with peer to peer trading of electric energy.

Content of this report was written solely by the authors. This includes the selection of topics covered in this report, modelling procedure, results and conclusions. The report does not necessarily represent the opinion of EUSALP Action Group 9.

1.1 Renewable electric energy

Renewable energy is energy, derived from renewable sources, which are naturally replenished in short time. European legislation [1] promotes the use of renewable energy through the Renewable Energy Directive and other documents. The EU has committed itself to a significant reduction in greenhouse gas emissions. The 2020 Climate and Energy Package of the European Union has settled the 20-20-20 goals comprising a 20 % reduction of greenhouse gases by 2020 compared to 1990, as well as a 20 % increase of energy efficiency and renewable energy sources at European level [2]. EU member countries have also taken on binding national targets for raising the share of renewables in their energy consumption by 2020 under the Renewable Energy Directive [3]. These targets vary, to reflect countries' different starting points for renewables production and ability to further increase it.

The European 2030 climate & energy framework [4] builds on the 2020 climate and energy package and further sets three key targets for the year 2030. By 2030, greenhouse gas emissions according to [4] shall be cut by at least 40 % (from 1990 levels), the share of renewable energy consumption shall at least reach 27 % and energy savings should account for 27 % compared with a business-as-usual scenario. In June 2018, a political agreement has been reached to raise the targets for renewable energy and energy efficiency to 32 % and 32.5 %, respectively [4].

The long-term strategy for the EU is to become nearly carbon neutral and to reduce greenhouse gas emissions to 80 - 95 % below 1990 levels by 2050 [1]. The EU Energy Roadmap 2050 [1] explores the challenges posed by delivering the EU's decarbonisation objective while at the same time ensuring security of energy supply and competitiveness. Several scenarios to achieve an 80 % reduction in greenhouse gas emissions have been examined. All imply major changes in, for example, carbon prices, technology and networks. All scenarios show that electricity will have to play a much greater role than now (approximately doubling its share in final energy demand to 36 - 39 % [1] in 2050) and will have to contribute to the decarbonisation of transport, heating and cooling. Electricity could provide up to around 65 % of energy demand by passenger cars and light duty vehicles, as shown in various decarbonisation scenarios. The share of renewable energy (RES) rises substantially in all scenarios, achieving at least 55 % in gross final energy consumption in 2050 [1]. The share of RES in electricity consumption reaches 64 % in a high energy efficiency scenario and 97 % in a high renewables scenario that includes significant electricity storage to accommodate varying RES supply even at times of low demand.
Table 1 summarizes current and future target shares of RES for the EU and for the states and regions of the EUSALP. Similarly, table 2 gives shares of RES in electricity. Binding targets in the EU are defined for RES, whereas RES in electricity targets are a matter of individual states strategies for achieving the RES goals.

Table 1: Current and future share of RES in EUSALP countries and EU

	2016 [7]	2020 [7]	2030 [7b]	2050 [1]
EU	17 %	20%	32%	min. 55%
Germany	14.8 %	18%	30 %	
France	16.0 %	23%	34%	
Italy	17.4 %	17%	30%	
Austria	33.5 %	34%	45-50 %	
Slovenia	21.3 %	25%	27 %	
Switzerland	22.1 %	25%	**	
EUSALP	18 % *			

* data for 2015 [10]

** we did not find relevant % data for Switzerland for the year 2030, according to [7c] the RES is expressed as produced energy 37.400 GWh for hydro power plants and 11.400 GWh for other RES.

Table 2: Current and future share of RES in electricity [12]

	2016 [12]	2020 [11]	2030 [4]	2050 [1]
EU	29.6 %	33.9 %	45%	64%-97%
Germany	32.2 %	38.6 % *	65%	
France	19.2 %	27 % *	40%	
Italy	34.0 %	26.4 % *	55%	
Austria	72.6 %	70.6 % *	100 %	
Slovenia	32.1 %	39.3 % *	47 %	
Switzerland	54.9 %	**	**	
EUSALP	40 % *			

*Data for 2015 [10]

** we did not find relevant % data for RES in electricity for Switzerland.

1.2. Production and demand

Renewable energy sources RES (wind, photovoltaics, biomass, waste, geothermal and others) and conventional electricity sources (gas, coal and nuclear power plants) work together in electric power system to provide electric energy, which is used by consumers. Electric energy directly can't be stored in an efficient way. At any moment in time, energy consumption perfectly matches energy production as shown in Figure 2. That means that the amount of power generated at any moment in time equals the power consumed. The balance in electric energy generation and consumption is required to maintain the stability of electric power systems. The stability of electric power systems enables today's lifestyle and perception of average EU citizen about fair and nearly unconditional availability of electric energy.

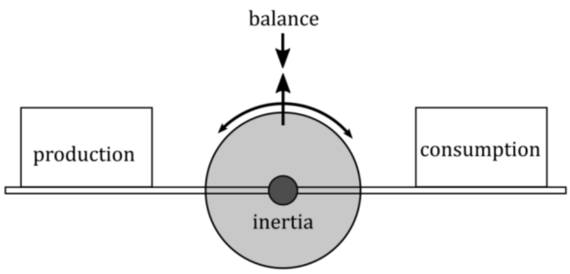

Figure 2: Electric energy production and demand always perfectly match. This may be represented by a balance with inertia. The electric power system has a certain inertia, enabling it to stay in balance despite small disturbances.

Large synchronous generators such as in nuclear and coal plants have traditionally provided stability by frequency control by a very high inertia of rotating parts (turbines and generators). As these power plants

will in the future gradually leave the electric power system, there may be a need for another service to maintain power system stability. We will not discuss electric power system stability in this report except from the viewpoint of continuous matching of production and demand.

1.3. RES share in electricity

Electric energy production from renewable sources is an important part of the Renewable Energy Directive [3]. The Renewable Energy Directive, together with other documents [among them data from 2, 3] provides much needed framework for sustainable development of EU energy sector, therefore several implementation aspects must be discussed.

The most common RES in electricity in the EU and in the EUSALP are wind, photovoltaics (PV) and hydro energy, with other sources like biomass and geothermal being currently much less important. Among RES, wind and PV energy production is dominated by environmental factors and daily and seasonal variations. Wind and PV are intermittent energy sources, that are not continuously available for the conversion into electricity, with the operator having no control on electric energy production. Intermittent energy sources can be to some extent predictable but cannot be dispatched according to the demand of an electric power system. Dispatchability is the ability of a given power source to increase and decrease output quickly on demand. The use of intermittent sources (wind and PV) in an electric power system usually displaces conventional electric energy generation or is optionally stored, or as the third option by the sector coupling used by electric heating for district heating schemes.

According to the Renewable Energy Directive [3], electricity from renewable sources must be bought by the electric grid operator regardless of the consumption and requirements in the electric power system. As the production of electric energy must always equal its consumption, conventional power plants (nuclear and thermal) nowadays change their power generation to allow for sudden reduction or increase of generation from renewable sources. As the renewable sources are highly unpredictable and intermittent, the conventional energy sources must adapt with the same timescale and intensity. We should bear in mind, that conventional energy sources were not designed for such intense variations and that their lifetime and efficiency therefore is compromised by such operation. Conventional energy sources are (and must be to perform efficiently) very large and stable to provide stable frequency and voltage of the electric power system. In the case of variations in the electric power system, their large and very fast rotating mass can

counteract changes in consumption or production (Figure 2) by the very large angular momentum. European electric grid or any other large network currently does not have other possibility to cope with huge variation in electric energy production.

To promote RES in EU all electric energy from RES are currently accepted into the electric network and bought regardless of demand and requirements of the electric power system. With much increasing share of RES in electricity, in the future there will be periods, usually during sunny and windy days, when electricity generation using RES will be higher than demand and storage capability. Some of the electric energy will have to be rejected, meaning there will be a surplus of RES generation. Some of surplus RES electricity generation may be used in HVAC (heating, ventilation and air conditioning) applications to locally store heat or run air conditioning devices, however in limited amount. It is therefore for future scenarios convenient to set % RES based on **used** and not generated electric energy according to

$$\% RES = \frac{RES\ elect.used}{total\ elect.used} \cdot 100\% \qquad Eq.\ 1$$

Without the use of Eq. 1, high RES scenarios may still feature large conventional generation and even larger share of surplus RES electric energy.

PSH (pumps storage hydro) is the largest energy storage technology in Europe (and indeed, worldwide). Currently, more than 50 GW net pumped hydro storage capacity (around 30 % of global capacity) is in operation in the EU, representing 12 % of total net electrical installed capacity in the EU [5]. By 2020, installed PHS capacity in Europe is expected to rise almost by 16 % [5 and 6], since PHS is the most mature and cost-effective large-scale storage solution available in Europe today.

1.4 Available energy storage in current reservoirs in the EUSALP region

To achieve the future target shares of RES electric energy production and considering daily, seasonally and yearly variations of available wind, photovoltaic as well as electric energy from hydro energy production, it is very important to determine how much energy storage is available in water reservoirs of existing power plants. Despite the number of different technologies of electric energy storage (reviewed later in section 4), only a PSH technology can store large enough amount of energy and provide long term (hourly,

daily and season) balancing. For analysis of future scenario of production-consumption ratio and its variation, determination of currently available energy storage in water reservoirs give a useful basis for an assessment of how much of water storage is required.

Regarding topographic and climate conditions there are several areas in the EU (e.g. Alpine Space, Pyrenees, Apennines) with a high potential for further construction of pumped hydro storage systems, but due to the central EU position and favourable topographic and climate conditions the Alpine space has strong advantage for electric energy generation and its storage using (pumped storage) hydropower plants with accumulations [14]. Climate conditions (e.g. high amounts of annual rainfall) and topography (e.g. river network and high elevation differences) of the Alpine region provide favourable conditions for high head hydropower plants (great amount of water masses, potential for storage capacity in reservoirs and consequently electricity generation). For analysis of exploitation of hydropower potential, we used different available data sources, while for assessment of current storage capacity in reservoirs in the Alpine space the ICOLD database of large dams and Global Reservoir and Dam (GRanD) database were used. The number of active hydropower plants, their installed capacity and mean annual energy production was determined based on HPP companies reports, available descriptions of HPPs etc.

Currently, there are more than 700 large reservoirs and more than 1000 operating hydropower plants in the Alpine region. Purpose of around 85 % of reservoirs is exclusively or partially hydroelectricity generation. Other purposes of reservoir are flood control, water supply, fish farming, recreation, artificial snowmaking and others. The total storage capacity of all reservoirs in the EUSALP region is 17 x 10^9 m^3 and more than 14 x 10^9 m^3 is capacity of reservoirs purposed for hydroelectricity production. For determination of storage capacity data of utilizable reservoir volume was obtained from technical sheets of HPPs (where available) or was assessed from known characteristics of reservoirs (area of reservoir, allowed variations in water levels in the reservoirs etc.). In the table below for each country in the EUSALP region are data about number of reservoirs, their area and volume capacity, and their catchment area.

Table 3: Total volume capacity and area of reservoirs and area of catchments for each country.

Country	Number of Reservoirs	Reservoirs capacity	Area of reservoirs	Catchment area
	[/]	[10^9 m^3]	[km^2]	[10^3 km^2]
Austria	147	1.946	140.2	396.165
France	82	4.364	169.2	130.963

Germany	47	0.808	70.5	14.271
Italy	197	3.104	460.4	51.662
Slovenia	13	0.095	13.5	59.136
Switzerland	121	3.580	102.2	11.517
Total	607	13.90	956.0	663.7

As large dams are essential to store water, which is used for peak load electricity generation, beside storage capacity of reservoir itself, an annual inflow is important for assessment of possible annual mean energy production. As this data was not available and such analysis would extend beyond scope of this report, area of upstream catchment draining into individual reservoir in square kilometers was determined. This data can be later used in detailed analysis of annual inflow volume estimation. Figure 3 shows the distribution of country-by-country storage capacity according percentage over the entire volume capacity purposed to hydro electricity production.

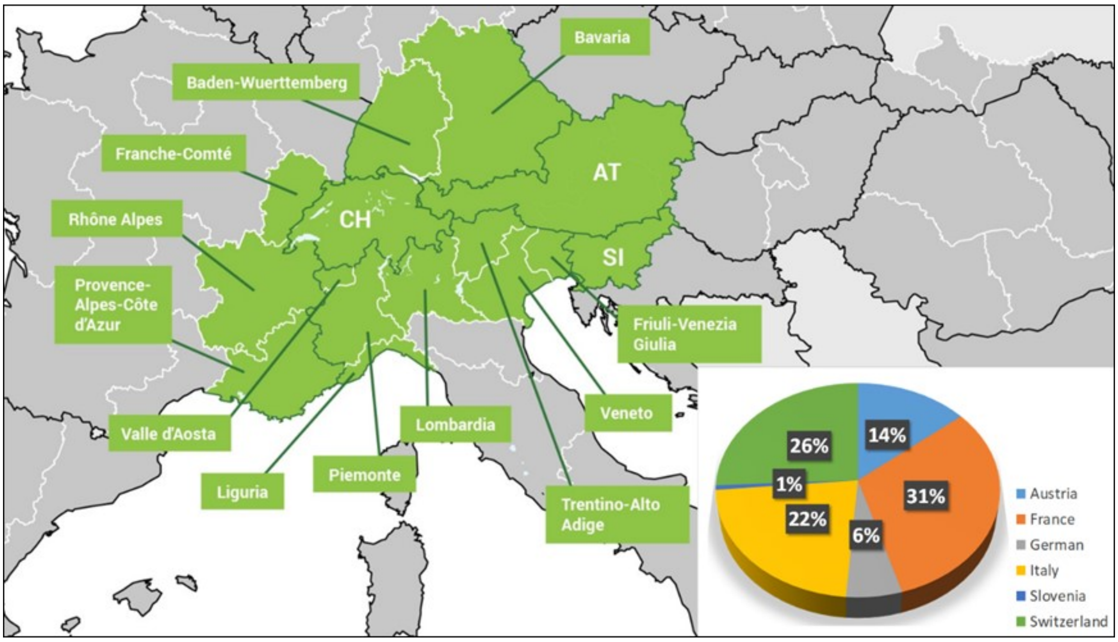

Figure 3: Distribution of country-by-country storage capacity according percentage over the entire capacity purposed to hydro electricity production.

While some reservoirs together with HPP form independent units, some reservoirs are connected in integrated systems (among them e.g. Cleuson-Dixence complex). According to different databases, reports

and analysis around 1021 hydropower plants of 5 MW or greater are in operation in the Alpine space (small (< 5 MW) and micro (< 10 kW) HPPs are not included). Table 4 gives detailed numbers of HPP in Alpine region [15].

The most common types of hydroelectric power plants are impoundment (33 %), run-in-the-river (53 %), diversion facility as well as pumped storage power plants (8 %). While with impoundment, run-in-the-river and diversion facilities base load electric energy is produced in a sustainable way, high head pumped storage power plants with their high capacities are suitable for peak load electricity production, flexible grid regulation and energy storage capacities. Just in Austria currently 26 pumped storage power plant (with an overall installed capacity 5071 MW) are in operation and 10 are in design or construction phase [21].

Table 4: Total installed HPP capacity and annual electric generation for each country in Alpine space.

Country	Electric installed capacity	Mean annual energy production
	[GW]	[TWh/ year]
Austria	10	20
France	9	17
Germany	3	2
Italy	12	30
Slovenia	1	3
Switzerland	10	25
Total	45	97

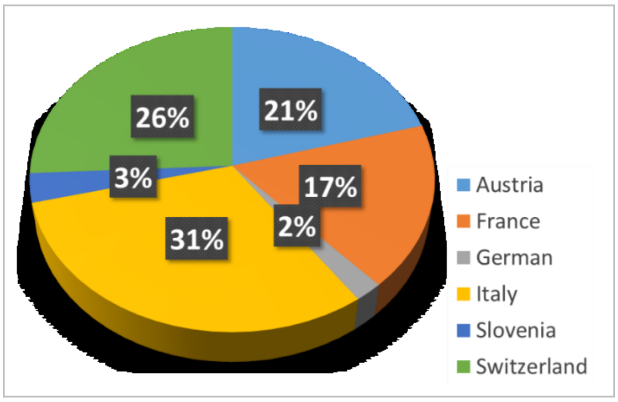

Table 5: Number of HPP in Alpine region (considering HPP of 5 MW or more).

Country	Run-of-the-river	Impoundment	PSHPP	Total
	[/]	[/]	[/]	[/]
Austria	115	53	26	194
France	110	73	6	188
Germany (Alpine region)	104	2	9	115
Italy	118	136	16	270
Slovenia	18	4	1	23

Switzerland	138	71	22	231
Total	603	338	78	1021

Total currently installed capacity of HPPs in the Alpine region (HPP of 5 MW or greater and without small and micro HPPs) is estimated at around 63 GW, and annual energy production close to 166 TWh [15]. For each country in the tables 5 and 6 data of installed capacity and mean annual energy production are given. For each country only HPPs in the EUSALP region are considered.

Table 6: Total installed capacity of HPPs in countries of the EUSALP region.

Country	Run-of-the-river	Impoundment	PSHPP	Total
	[GW]	[GW]	[GW]	[GW]
Austria	4,7	3,8	5,1	13,1
France	6,6	6,4	3,6	16,6
Germany (Alpine region)	2,2	0,2	1,9	4,3
Italy	2,4	6,6	5,1	14,1
Slovenia	0,9	0,1	0,2	1,1
Switzerland	3,5	7,1	3	13,5
Total	68	24,1	18,7	63,2

Table 7: Average annual output of HPPs [TWh] in countries of the EUSALP region.

Country	Run-of-the-river	Impoundment	PSHPP	Total
	[TWh]	[TWh]	[TWh]	[TWh]
Austria	25	8	3,8	36,7
France	32,9	15	1,7	49,6
Germany (Alpine region)	12,1	0,4	0,4	13
Italy	9,7	16,6	1,8	28
Slovenia	3,5	0,5	0,5	4,5
Switzerland	15,3	16,4	2,8	34,6
Total	98,6	56,9	11	166,4

1.5 Transmission and distribution of electric energy and peer to peer trading

The way how electric energy comes from the producer to the user is composed of two parts, transmission and distribution grids. Current situation is schematically shown in Figure 4. Electric power transmission is the first part of delivery of electric energy from the large to the transmission system connected power plant. Electric power distribution is the second and final stage in the delivery of electric energy. Electric energy distribution system delivers electricity from the transmission system to individual consumers. The distribution system connects to the transmission system and lowers the transmission voltage to low voltage of 400 V with the use of transformers.

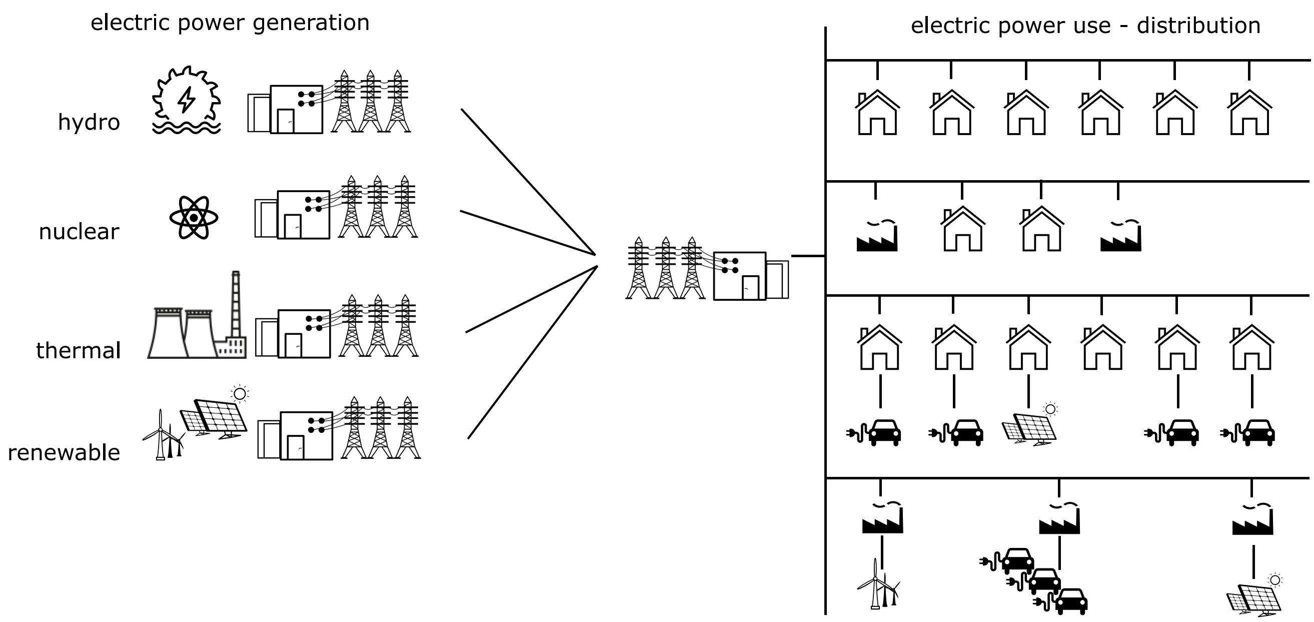

Figure 4: Schematics of current transmission and distribution of electric energy.

Currently, electric energy distribution companies perform service of distribution, which involves maintenance of the distribution electric network and selling of electric energy to consumers. As photovoltaics, wind and other intermittent RES electric energy sources increase, and battery storage systems emerge, the idea of peer to peer electricity trading was born. Peer to peer trading of electric energy (shown in Figure 5) represents a major deviation from established praxis of traditional role of electric energy distributor. The

passive role of a consumer subjected to market rules is as such no longer necessary. As new technologies emerge, householders identify potential sellers or buyers. The peer to peer trading of electric energy is based on smart contracts between producers and users of electric energy. The main advantages are:

- no middle man and parties make deals on their own terms,
- instantaneous access to production and consumption of individuals within the distribution grid,
- producers and users both have lower costs and
- transparent electric energy trade directly with other consumers can be performed.

Actual trading within peer to peer contract is performed based on smart contracts between producers and consumers, that are enabled by blockchain technology.

Peer to peer trading of electric energy adds requirements to the current transmission and distribution systems for electric energy supply for individual producers and consumers like internet connection, smart metering, inverters for regulation of energy production (Figure 5), trading software etc. Peer to peer trading system in Figure 5 has energy storage implemented only on production level.

We believe that the market of electric energy will evolve in the direction of peer to peer trading in the following years up to 2050. Due to the complex task of legislative regulation of smart contracts among producers and users, we believe regulating institutions must start adapting to the emerging peer to peer trading method immediately. The regulators will need to adapt to this new peer to peer trading platforms to be able to cope with the market development. The role of regulators is extremely important, they also have much responsibility for electric power system stability with ever increasing share of RES in electricity production. In the future, peer to peer trading networks will be upgraded with electric energy storage option.

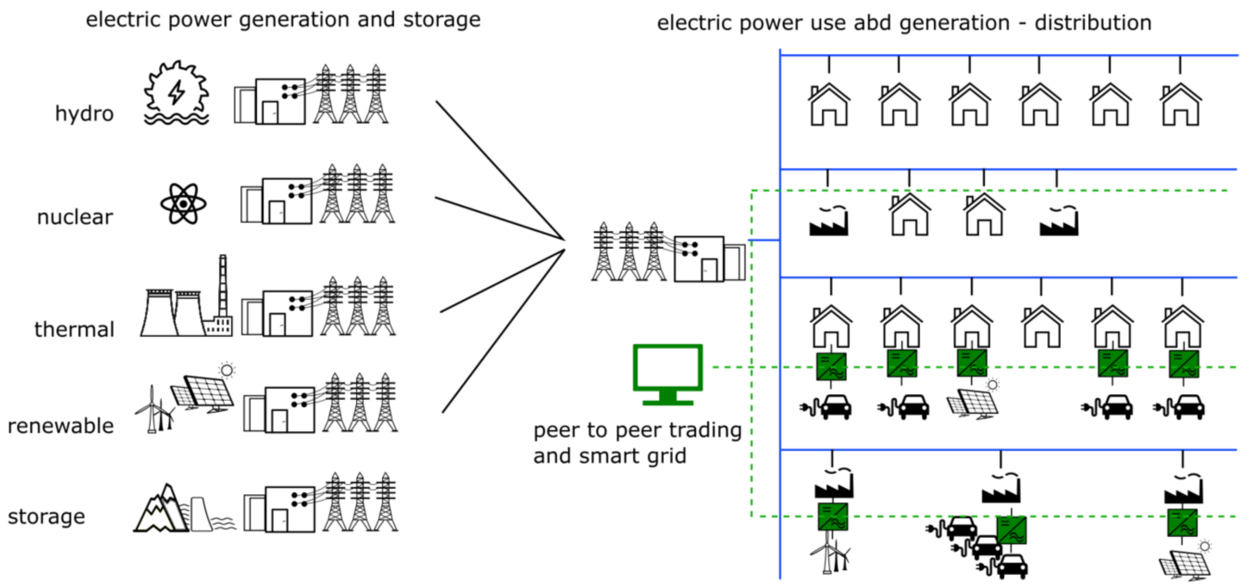

Figure 5: Peer to peer trading of electric energy. Note energy storage is only present on generation level. Peer to peer trading helps to distribute energy loads on distribution level, as individual lines are very unevenly loaded. Not all energy lines necessarily participate in peer to peer trading.

1.5.1. Business case of peer to peer trading

Currently, peer to peer technology is being advertised and introduced because of lowering costs for producers and users of electric energy. We believe there may be more into it.

The peer to peer electric energy trading methodology is very new and sometimes it is difficult to understand the business case of the peer to peer trading method. For instance, SunContract peer to peer platform from Slovenia does not charge significant costs for "connection" of producer and buyer, while some other peer to peer providers do so. The business case not is not clearly revealed by the service providers and we speculate where the income will in the future come from.

The most important development of peer to peer trading will be related to instantaneous measurements of production, storage and consumption of electric energy at the distribution level. Knowing customer's electric energy usage habits will enable improved demand side management, sector coupling and storage strategies, enabling companies implementing peer to peer trading. By doing so, energy will be better utilized and consumed at lower and sold at higher prices for the entire peer to peer network.

Next possible business case scenario for peer to peer network is based on improved utilisation of distribution system elements like transformers, conductors etc. Smart trading of electric energy will decrease costs of upgrades, which will be required to many European distribution networks with the advent of electromobility, increase of HVAC for heat pumps cooling and heating, and distributed generation of electric energy by PV modules. As we will show later in section 3, in a very likely future scenario, electric energy from RES sources may be rejected, implementation of this may be also performed within peer to peer trading platform.

Another possible business case of peer to peer network is reactive power management. Reactive power management becomes increasingly important with general transition from resistive loads to inductive loads. PV modules are connected to electric grid using frequency inverters, which act as an interface between the PV power plant and the network. Many of such devices can be set such, that reactive power load for the grid is improved. Nowadays, for instance average small residential PV power plant isn't "aware" of electric power system and distribution network requirements, and inverter settings are constant and preset. Knowing requirements of the electric grid, peer to peer trading can help in improving reactive power management.

As shown above, peer to peer networks may be transformed into powerful smart grids. The above listed services may also generate a very high revenue to peer to peer networks providers.

Conclusions for section 1:

- The EU is committed to significant increase in share of renewable energy sources in electric energy generation, leading to possible surplus of electric energy generation,
- with a high share of renewable energy sources, for future scenarios it will be fair to set % RES based on used and not generated electric energy,
- the EUSALP region features favourable conditions for hydro power plants including pumped storage,
- peer to peer trading has the potential to evolve into powerful electric energy trading network due to network diagnostics, improved utilisation of distribution network, reactive power management etc.

2. PSR MODELING METHODOLOGY

The increase of RES in electricity until 2050 [1] will require, that electric energy storage will increase. To estimate the storage requirement, the PSR (pump storage requirement) model was developed. The aim of the PSR model is to estimate requirements for energy storage to give guidelines for stable and reliable electric energy supply in the EUSALP region. The PSR model does forecast requirement for energy storage but does not specify type of energy storage. The type of energy storage will be further discussed in section 4. We have assumed that the energy power transmission capacity over power lines is unlimited and that energy produced in for instance, France in Grenoble, is immediately available in, for instance, eastern Austria around Vienna.

The PSR model is not limited to various scenarios of future electric energy production and consumption. Instead, the ***scenarios*** may be inserted in the model as inputs and boundary conditions, while the PSR model will calculate the requirements for energy storage for these inputs and boundary conditions.

In the model, we addressed only ***technical*** production and demand. So, whenever the electric energy is produced by wind or photovoltaic sources and storage capabilities are available, energy storage capabilities are used. Also, whenever there is demand and electric energy is produced it is used to cover demand and this energy is not stored. Electric energy is thus stored always in cases, where energy production is higher than consumption and storage capabilities are not full. We did not at all address cases, when market prices may introduce anomalies like reduced consumption due to too high prices or reduction or delay in pumping for instance in the case that pump turbine operator will wait for more financially favourable conditions and not use storage capabilities immediately. Market financial influence may further increase electric energy storage requirements in comparison with PSR model calculated technical requirements.

Also, in the PSR model, the response time of all energy storage sources is assumed to be infinitesimally short. With an extension of the PSR model with small modifications of the existing model, one will be able to estimate financial benefits of electric energy storage in the EUSALP, offered as a service to other European regions like, for instance, Northern Germany, rich in intermittent wind and photovoltaic electric energy production.

2.1. Datasets of current electric energy production and demand

Before we can model future development of energy production, demand and storage, we must provide the data about current energy production and demand.

In the PSR model, we have used the data of average energy production over the entire year in hourly intervals. Generation and consumption power (power in GW) within hourly intervals also represent energy generation and consumption (energy, in GWh or TWh). Several consecutive years were evaluated as shown below in Table 8. The datasets for existing average consumption of electric energy were found in the following literature as also shown in Table 8.

The model was based on available data for different production sources:

- wind,
- photovoltaics,
- run of river hydro,
- PSH with inflow,
- small hydro,
- other RES sources,
- fossil fuel power plants and
- nuclear power plants.

Among those, we label fossil fuel and nuclear power plants as conventional, other are renewables (RES). Nuclear power plants installed power was evaluated for each power plant within EUSALP region separately and derived from [15]. Coal and gas fired power plants installed power was found in [15]. Capacity factors for conventional sources was estimated from the values for capacity factors for nuclear power plants from data from individual power plants and from [15].

Table 8: Dataset sources and years for EUSALP countries and regions

Region	demand	sources
Austria - entire country	[19]	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18], profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19] other RES: [19]

		conventional sources: [15]
Slovenia - entire country	[19]	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18], profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19] other RES: [19] conventional sources: [15]
Germany - Bavaria, Baden Württemberg	[19, 20], for entire Germany, adjusted for region	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18], profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19], profiles for Germany were used other RES: [19] conventional sources: [15]
Italia - Valle d'Aosta, Piedmont, Liguria, Lombardy, Trento, Veneto, Friuli Venezia Giulia, Alto Adige/Südtirol	[19], for entire Italy, adjusted for region	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18] profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19], profiles for Italy were used other RES: [19] conventional sources: [15]
France - Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté, Provence-Alpes-Côte d’Azur	[19], for entire France, adjusted for region	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18], profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19], profiles for France were used other RES: [19] conventional sources: [15]
Switzerland - entire country	[19]	wind: [15, 16, 17, 18], profiles for years 1980-2016 PV: [15, 16, 17, 18], profiles years 1985-2016 hydro: [15], profiles and ecological minimum [19] other RES: [19] conventional sources: [15]

Liechtenstein	not considered	not considered

2.1.1 Wind and photovoltaics datasets

For wind and photovoltaics hourly production ratio was included the model in the following way. Wind and photovoltaics production were averaged day by day and hour by hour over all available years. Yearly averaging was performed on individual EUSALP regions from Table 8, while the data of individual EUSALP countries and regions were later summed up to give the whole EUSALP amount. The wind and photovoltaics energy production profiles show daily (day/night) and yearly (winter/summer) variations of available solar exposure and wind occurrence.

The wind and photovoltaics hourly production ratio are shown as a ratio (0 - 1) of the installed power. Thus, in any future scenario projected installed power (for instance for photovoltaics and for year 2040) was multiplied with averaged hourly production ratio for each hour of the year to give the PV generating power for selected hour and scenario.

We need to comment on averaging of wind and photovoltaics datasets with the PSR model. Clearly averaging over years introduces smoothing in datasets. Any real-life scenario of yearly wind and photovoltaics situation will likely introduce higher fluctuations than those used in the PSR model.

Electric energy production from wind and photovoltaics sources will in PSR model show high variations, which correspond to real future scenarios.

2.1.2 Hydro power plants production datasets

The available production from various types of hydro power plants HPP is based on installed power, amount of water available (discharge) in upper accumulation and available head.

We were able to estimate well installed power of HPP according to [15]. Discharge on the other hand can't be easily estimated, because it varies with time of the year. Yearly variation of river water flow rate is reflected in monthly HPP production diagrams. For the PSR model, yearly HPP production diagrams were used to estimate the yearly variation of available energy from run of river and storage with inflow HPP. Yearly HPP production diagrams available to us only show data in one-month intervals, introducing a non-continuous variation between months and thus affecting PSR model results. To mitigate this problem, monthly HPP production values were for each EUSALP country or region averaged such that a low order (second or third order) polynomial was fitted over HPP production datasets. The polynomial was introduced

for both run of river HPP and storage with inflow HPP. Averaging was done in such a way, that yearly production of original and averaged values was the same.

We must note the following limitations of to us available data (Table 8):

- HPP production diagrams for Baden Württemberg and Bayern were not available, so we have used HPP production diagrams for Germany instead,
- HPP production diagrams for Auvergne-Rhône-Alpes, Bourgogne-Franche-Comté and Provence-Alpes-Côte d’Azur were not available, so we have used the HPP production diagram for France instead and
- HPP production diagrams for Valle d'Aosta, Piedmont, Liguria, Lombardy, Trento, Veneto, Friuli Venezia Giulia and Bozen were not available, so we have used the HPP production diagram for Italy instead.

Yearly variations in produced energy in HPPs are large, for instance in Switzerland in February only 30 % of installed run of river HPP power is used, while in summer this value is over 75 %.

The minimum environmental flow rate for run of river hydro was estimated for each period of the year based on the minimum recorded hourly production of electric energy from the same data as shown in Table 8.

2.1.3. Datasets for other renewables

Production, installed power and availability of other renewable sources of electricity is difficult to estimate. Among other renewables are biogas plants, geothermal etc. power plants. We have in the PSR model estimated, that other renewables produce electricity continuously. Other renewables contribute little to overall electric energy production.

2.1.4. Conventional electricity sources datasets

Production from conventional electricity sources comprises of gas, coal and nuclear thermal power plants. No differentiation was performed between nuclear and other thermal power plants. The amount of conventional electricity sources was within the PSR model selected such that % of RES in total production is met. Also, conventional electricity sources are assumed to be always available whenever required.

2.1.3. Electric energy consumption

Electric energy consumption estimation was based on the data provided in Table 8. The hourly data for some regions was not available, among them Italy, Germany and France regions. What was available, were hourly data for entire countries Italy, Germany and France.

For the German region of the EUSALP, we have estimated total yearly consumption to 74 TWh for Baden Württemberg and 78 TWh for Bayern according to [19]. The hourly consumption for the German part of the EUSALP was calculated as hourly consumption ratio for Germany, multiplied with yearly consumption for Baden Württemberg and Bayern. Baden Württemberg and Bayern account for approximately 30 % of entire German energy consumption. Same procedure was applied for Italy and France. The demand for each year must be the same as production plus import minus export.

2.2. PSR model features

In the subsection 2.1, we have considered existing energy production and demand. How the electric energy production and consumption in the future will affect the operation of the PSR model, will be discussed in this subsection. The prerequisites are modelling assumptions how the energy supply and consumption will evolve in the future.

In the PSR model we have assumed that electric residential, public and industrial energy consumption in the future will approximately remain constant. We justify this by the reasoning, that future decrease in energy consumption due to more efficient machines, devices and processes will be offset by increasing requirements of HVAC systems (heat pumps for heating and cooling being used instead of gas, oil or biomass heating and ever-increasing need for cooling in summer months due to global warming). In addition to this, we have assumed that electric energy consumption from the use of electric cars will increase with the number of electric cars gradually increasing.

2.2.1 Electric cars

Electric cars will be part of European future if we want to limit CO_2 emissions to reasonable levels and be self-sustainable and energy independent from oil producing countries. Electric cars have batteries, and these must be regularly charged. We have included in the PSR model the following features:

- electric cars can be charged in pre-selected variable pattern over the day, however this pattern cannot change from one day to another except for the weekends (Saturday and Sunday),

- a selectable percentage of total electric energy stored in car batteries may be taken from car batteries when required at any time of the day (flexible charging),
- percentage of electric cars (number), consumption of electric energy per 100 km, and yearly mileage can be adjusted,
- in the PSR model we have assumed that consumption of electric energy per 100 km equals 20 kWh [24],
- every electric car must charge the battery every day to the amount of energy, which is used for driving the average daily "mileage" 39,7 km (14500 km/365 days), such action greatly improves battery life and should be performed whenever possible.

Some of the above properties were introduced to simplify the PSR model.

2.2.2. Wind and photovoltaics

For modelling, wind and photovoltaics was included in the model as a source of electric energy, which is generated whenever available, therefore not flexible at all. With the increase of RES share, we will arrive to the situation, when at selected time intervals the entire energy consumption will be covered by RES sources. For even further increase, besides covering consumption, RES production may be even too high for storage in PSH, hence we arrive to surplus electric energy. Surplus electric energy is the energy, that is generated by the wind and photovoltaics sources and which cannot be used or stored. This may be due to too low pumping installed power of PSH (power) or too low storage volumes of PSH reservoirs (energy) or both.

2.2.3 Hydro power plants

For hydro power plants, we have used a more flexible approach than for wind and photovoltaics. Hydro energy is available or stored on daily, weekly, monthly or yearly basis, depending on the water storage capacity and available power of HPP. Data are difficult to get or collect for individual HPP, so we have prescribed in the model the following assumptions:

- run of river hydro may use the water whenever required during the day or night except for the minimum environmental flow rate, required for each river,
- minimum environmental flow rate must always be provided,

- there is no limit on the denivelation speed of any water storage, that is any rate of change of water level in reservoirs is allowed,
- the maximum production power of run of river hydro is limited only by installed power of turbines and
- daily average production in run of river power plants must be equal to historical daily averages from the Table 8.

We must comment on the last assumption about daily average production in run of river power plants being equal to historical daily averages. The assumption underestimates actual flexibility of run of river power plants. However, we assume that yearly averaging of wind and PV production more than offsets it.

Efficiency of pump and turbine mode of operation may be set from $\eta = 0$ to $\eta = 1$. During all scenarios we have used efficiency $\eta = 0{,}85$ (both for pump and turbine mode of operation, combined $\eta = 72{,}2$ %) which includes all losses that appear in the storage process (transmission, transformer, generator, turbine, hydraulic and other losses etc.). Current HPP achieve max efficiency almost 80 %, among them for instance PSH Avče, Slovenija. However such efficiency is not available for all operating points, and generally units with high peak efficiency have slightly lower efficiencies away from best efficiency point than those with flat efficiency curves.

Pump storage hydro PHS with inflow and small hydro power plants SHPP were modelled using the same assumptions as run of river HPP.

2.2.4 Generation by fossil fuel power plants

Within the PSR model, we have included the ability to produce missing but required energy using conventional fuel sources. Conventional electricity sources are coal, nuclear and gas power plants. In the PSR model, all conventional electricity sources are treated in the same way. Usually, nuclear power plants cover base load, while coal and gas fired power plants cover slow daily variations in demand (intermediate peaking). The PSR model assumes, that renewable electricity sources are used whenever they are available. This is also the current situation in the electric power system in EU. We must notice also, that with high share of photovoltaics and around over 60 % of RES, in usual daily situation RES will cover the entire demand during the day. Conventional sources may be shut down completely in this time interval. This is the situation allowed and implemented in the PSR model. With current nuclear power plants, their operation does not allow for daily shutdowns for safety reasons. **Nuclear power plants are not suitable for high RES scenarios**.

Stability of the electric grid is nowadays provided by large conventional power plants. Large mass of fast rotating parts (very high rotational moment) allows for the compensation of variations in demand. There is currently no other method in operation available which will in short term substitute this form of provision of the electric grid stability. The PSR model does not deal with electric power system stability issues.
For future scenarios with more than 80 % RES little is known about share among different RES sources and role of conventional generation about electric power system stability. Because of the large number of unknown parameters, which will arise at high RES scenarios, we have limited the PSR modelling to max. 80 % of RES share in total electric energy consumption.

2.2.5. Import

Within the PSR model, we have included the ability to import electric energy from outside the EUSALP. This situation appears whenever RES production and generation from PSH is lower than installed power of conventional sources. Current installed power of conventional sources is more than enough to offset requirements for electric energy with over years much increasing share of RES. Costs of maintaining current conventional energy sources and difficulties in building new conventional power plants may prove to be a limiting factor in our efforts to keep current installed power of conventional power plants operational. In the PSR model we have assumed, that **installed power of conventional sources will decrease with years** such that % of RES in electricity will be achieved.

2.3 PSR modelling procedure

The PSR modelling procedure may be separated to inputs (A), modelling (B) and presentation and comparison of results (C) as described below.

A: inputs

- user sets installed power of PV, wind, fossil fuel, run of river HPP, PSH in turbine mode and pump mode of operation (in [MW]),
- user sets PSH pump and turbine efficiencies (in %),
- user sets PSH storage capacity (in [TWh]),
- user sets set percentage of electric cars and average yearly "mileage", for instance 50 % and 14500 km/year
- user sets parameter "storage from inflow flexibility" (on/off),
- user enables or disables flexible charging of EV (on/off) and

- user sets a disturbance in PV and wind generation (interval and power in [MW] of reduction in installed power).

B: modelling

The PSR model compares production with demand and:

- if production is higher than demand, use remaining electric power for electric storage,
- limit electric production from photovoltaic and wind if maximum storage capacity (all reservoirs full, max storage capacity reached) is reached,
- limit electric production from photovoltaic and wind if maximum storage power (all pumps running at full capacity) is reached and
- if production is lower than demand, use available stored electric power for electricity generation.

C: presentation and comparison of results

- The PSR model gives hourly variation of storage capacity (stored energy in [TWh]),
- RES (PV, wind) power factors are shown,
- shortage of electric energy is shown for installed power and energy for any time of year, while also max. installed power shortage (in [GW]) and total energy shortage (in [TWh]) are shown,
- total surplus of electric power (in [GW]) and total surplus of electric energy / year are shown,

The PSR model is available in the form of Microsoft Excel spreadsheet.

Consumption and generation of electric energy over the entire year must be the same. To achieve required % RES (Eq. 1), the model calculates, how much RES electric energy must be generated and how much RES installed power is required. The amount of required RES installed power we call RES power factor, because it is calculated as a multiplication with currently installed power. For instance, PV power factor 200 % means, that investigated scenario requires twice the installed PV power in comparison with current situation (2016). This is for individual scenarios expressed as PV power factor and wind power factor.

2.4 Climate change

The Earth's climate has changed throughout history several times. Recent change in climate has been especially intense. The current global warming situation is important because it is most likely to be the

result of human activities and is proceeding at a rate that is many times faster than historic global warming events.Global warming is by some sources estimated to lead to about 20 percent increase of the worldwide water scarcity increase until the end of century. The EUSALP region is not among the ones much impacted by potential water scarcity.

The PSR model does not include global warming and its consequences. Indeed, amount and availability of water in the EUSALP run-of river HPP may decrease in the future. This may decrease electric energy production in run of river HPP and PSH power plants with inflow. Pure PSH power plants, used for electric energy storage will be impacted less. The reduced electric energy production from HPP will make electric power system more vulnerable and variations in RES production will be more difficult to counter. Climate change will have negative impact on the electric power system. If energy storage in the EUSALP will be implemented using the PSH, water retention will be increased, having beneficial effects on reduction of water scarcity. In addition, available stored water in upper and lower reservoirs will be available for irrigation, ensuring ecological flow during droughts, river sport activities, fishing, potable water treatment etc., mitigating problems caused by climate changes and associated water scarcity.

Conclusions for section 2:

- PSR model allows for modelling of:
- **electric storage requirements,**
- **max. surplus electric power and energy,**
- **PV and wind factor requirement to maintain required RES share in electricity production,**
- **etc.**

- various scenarios of future energy production and consumption can be examined

3. ELECTRIC ENERGY STORAGE REQUIREMENTS - MODELLING RESULTS

The energy demand and production are currently still growing. Considering topographic and hydrological characteristics of the EUSALP region, hydropower potential is still enormous. Due to ecological, social, legal, political and other reasons the potential cannot be fully exploited. The EU should be aware, that future transition to PV and wind RES in electric energy production will trigger requirement for energy storage. In this section we will review requirements for energy storage in the EUSALP region.

3.1. Scenarios

The envisaged development of RES share in electricity production [1, 2, 3 and 4] in the EU is not firmly set. The RES share in electricity is not set by the European Union, but it is influenced by requirements in CO_2 emission reduction. Data from [1, 2, 3 and 4] suggest, that scenario shown in Figure 6 is probable. We have limited our model to RES share according to the Eq. 1. and to 80 % of maximum RES share. Figure 7 shows a probable scenario for share of EV in the total light duty vehicles EU fleet.

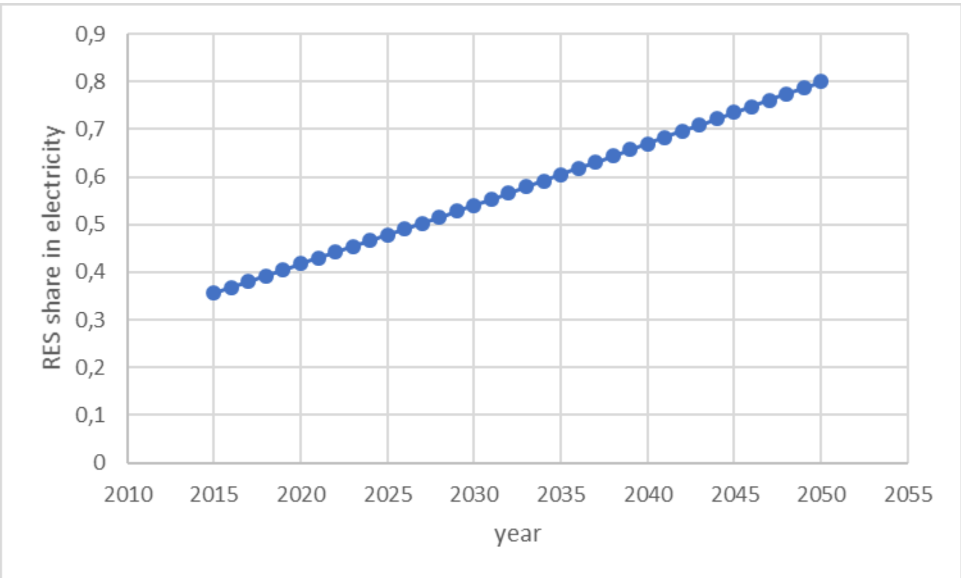

Figure 6: For PSR model envisaged development in RES share in electricity production.

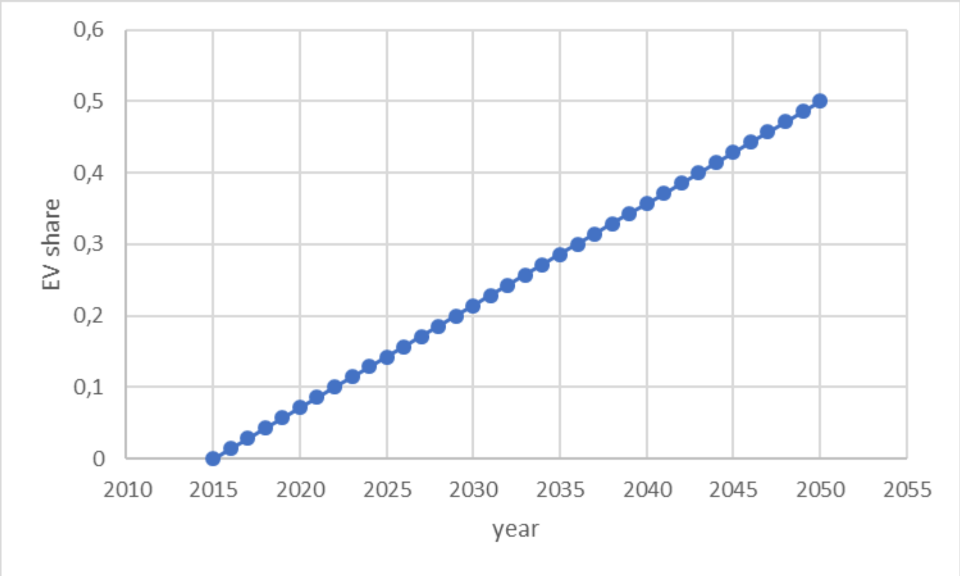

Figure 7: Chosen scenario for share of EV until 2050.

The list of scenarios is shown in Table 9. A total of twelve scenarios were selected for evaluation.

Table 9: List of modelled scenarios

Scenario [-]	ratio PV/wind [-]	EV [%]	disturbance [-]	storage share [%]
1	1	0	no	100
2	3	0	no	100
3	1	25	no	100
4	1	50	no	100
5	1	100	no	100
6	1	realistic	no	100
7	3	50	no	100
8	1	50	no	200
9	2	50	no	200
10	3	50	no	200
11	1	50	yes, 15 days	100
12	3	50	no	1000

These scenarios were selected among others because they represent well possible future developments of RES energy production. They are however not complete, real scenario is for now unknown and will be surely different than any of the above analysed scenarios.

3.2. PSR model results - hourly data samples

Figure 8 shows sample results of modelling using the PSR model for scenario 11 (Table 9) for the year 2050 and 80 % RES share. The scenario 11 assumes equal PV and wind share of 1215 % of installed power in 2016. Scenario 11 includes a disturbance of duration 15 days from 5th to 20th March. This interval was selected as very inconvenient because much of the energy storage is already consumed by then. In Figure 8 electric energy production is very high because of inconvenient generation of RES electricity sources; hence a lot of electric energy is rejected. Figure 8 also shows yearly variation in electric energy production because of high share of PV (envelope of daily production). Electric energy production is the highest during the summer. Short individual peaks are consequences of daily variation in electricity generation.

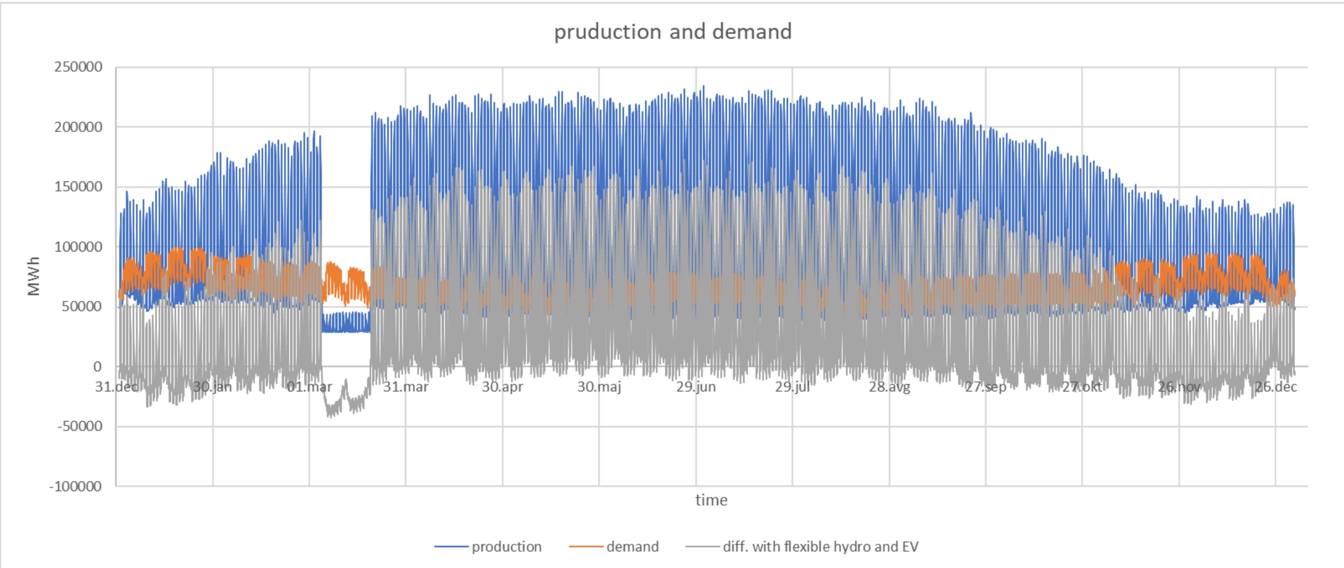

Figure 8: Sample production, storage and demand of electric energy for scenario 10 for each hour of the year 2050. Grey line shows difference between production and demand using flexible operation of HPP and use of EV batteries.

Figure 9 shows the amount of stored energy during the year 2050 for scenario 11. As explained in the previous section, the amount of storage within the entire study was unlimited (unlimited storable energy).

The power of storage power plants was limited. Each year must start and finish with the same amount of stored energy, the orange curve in Figure 9 ends at the same stored energy. Interestingly, grey curve shows amount of energy which could be stored, if power of energy storage power plants would be unlimited in addition to the unlimited storage capacity. Figure 9 shows, that a lot of RES production of electric energy is not used, we note this as a surplus energy.

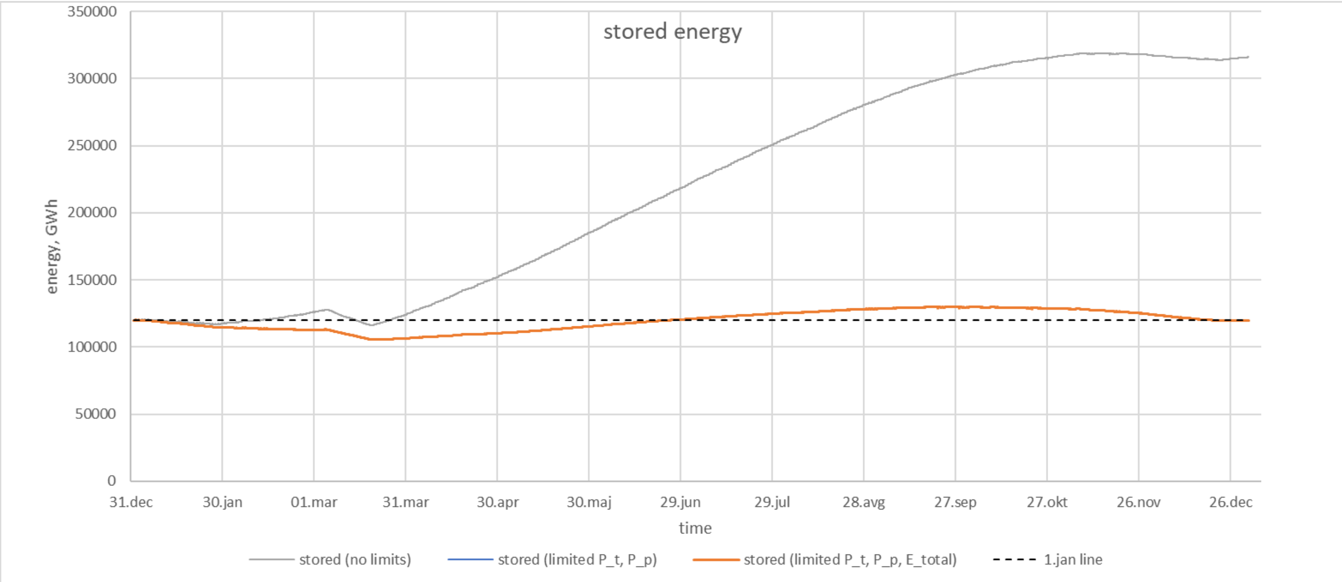

Figure 9: Sample amount of stored energy during the year 2050 for scenario 10. Grey line shows amount of stored energy under assumption of unlimited storage capacity, while orange line shows stored energy considering limitations due to finite power and energy of electric storage power plants. Data are available for each hour of the year.

Figure 10 shows daily shortage and surplus energy for the entire year 2050 and 80 % RES for scenario 11 from Table 9. We see that we have a lot of surplus of RES electric energy production, which can't be used or stored.

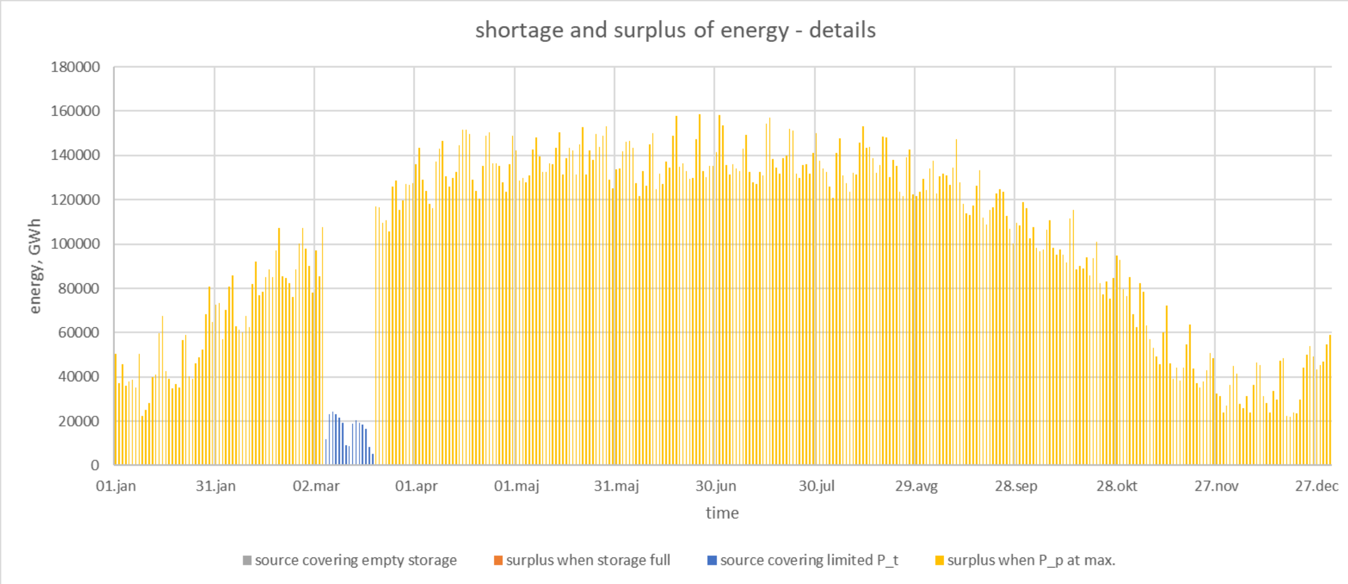

Figure 10: Sample results of PSR modelling of the shortage and surplus energy for the entire year for scenario 10. Data are available for each hour of the year.

3.3. PSR model results - dependence on RES share

Figures above of hourly data provide the basis for yearly analysis of individual scenarios from Table 9. The analysis includes calculation of PV and wind factors (required to achieve selected % RES values), total shortage (max. power [GW] and total energy [TWh]), total surplus (max. power [GW] and total energy [TWh]).

Result for scenarios 1 to 10 are shown from Figure 11 to Figure 22.

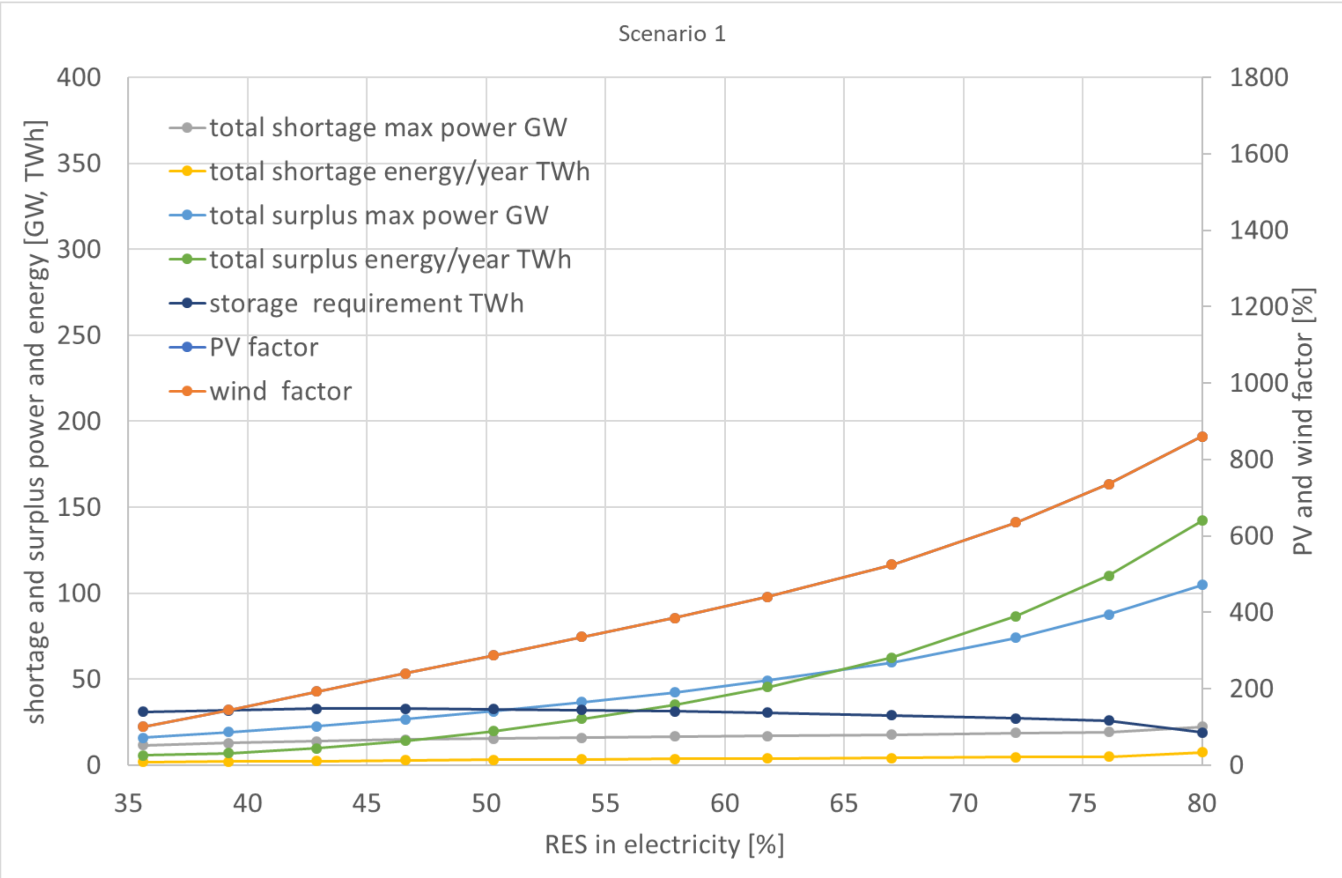

Figure 11: Scenario 1, PV : wind = 1 : 1 ratio of installed power, 0 % EV, storage share 100 %, no disturbance

Figure 11 shows the PSR model results for scenario 1 with PV : wind = 1 : 1 ratio of installed power, 0 % EV and no disturbance in RES electric energy production. Energy storage power and energy remain on the today's level. Results show low requirement for storage, which decreases with RES in electricity share, eventually to below 25 TWh. Low requirement for energy storage is a consequence of over-generation during the day with RES. Apparent low requirement for electric energy storage is caused by the much too low installed power of PSH (comparison with scenario 12). With over 800% of installed PV generating capacity in comparison with current situation, during the day enough electric energy will be available and storage will only be required to cover energy demand during each night.

In Figure 11 we also notice that some energy shortage will be present, and the shortage will be approximately constant for all RES shares.

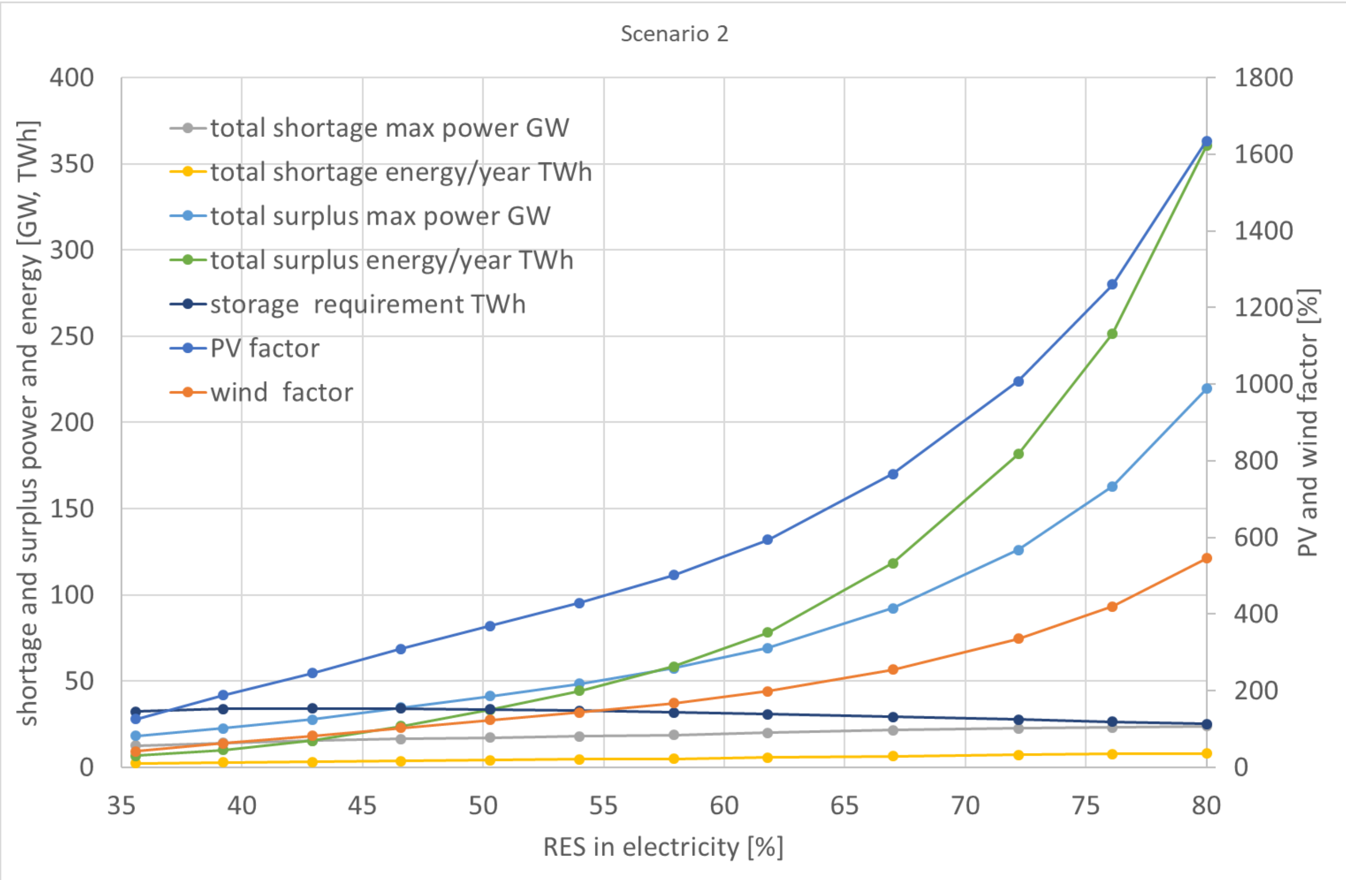

Figure 12: Scenario 2, PV : wind = 3 : 1 of installed power, 0 % EV, storage share 100 %, no disturbance

Figure 12 shows scenario 2 with ratio PV : wind = 3 : 1 of installed power and 0 % EV. Energy storage power and energy remain on the today's level. In comparison with scenario 1 with ratio PV : wind = 1 : 1 (Figure 11) we notice that to maintain high RES shares, a much higher installed power of PV is required, reaching more than 1600 % of currently installed power. Interestingly, wind factor is not much lower than for the scenario 1 despite set ratio PV : wind = 3 : 1.

Like in scenario 1, scenario 2 shows modest shortage of electric power and energy. The modest requirement for energy storage has similar roots as explained under scenario 1.

Scenario 2 shows that surplus electric energy generation is enormous. Yearly over 350 TWh must be rejected due to inability to store the electric energy and because much of the electric energy is generated at inconvenient time of year or day. High share of rejected electric energy from PV makes PV an extremely expensive and unattractive source of energy for high RES ratios.

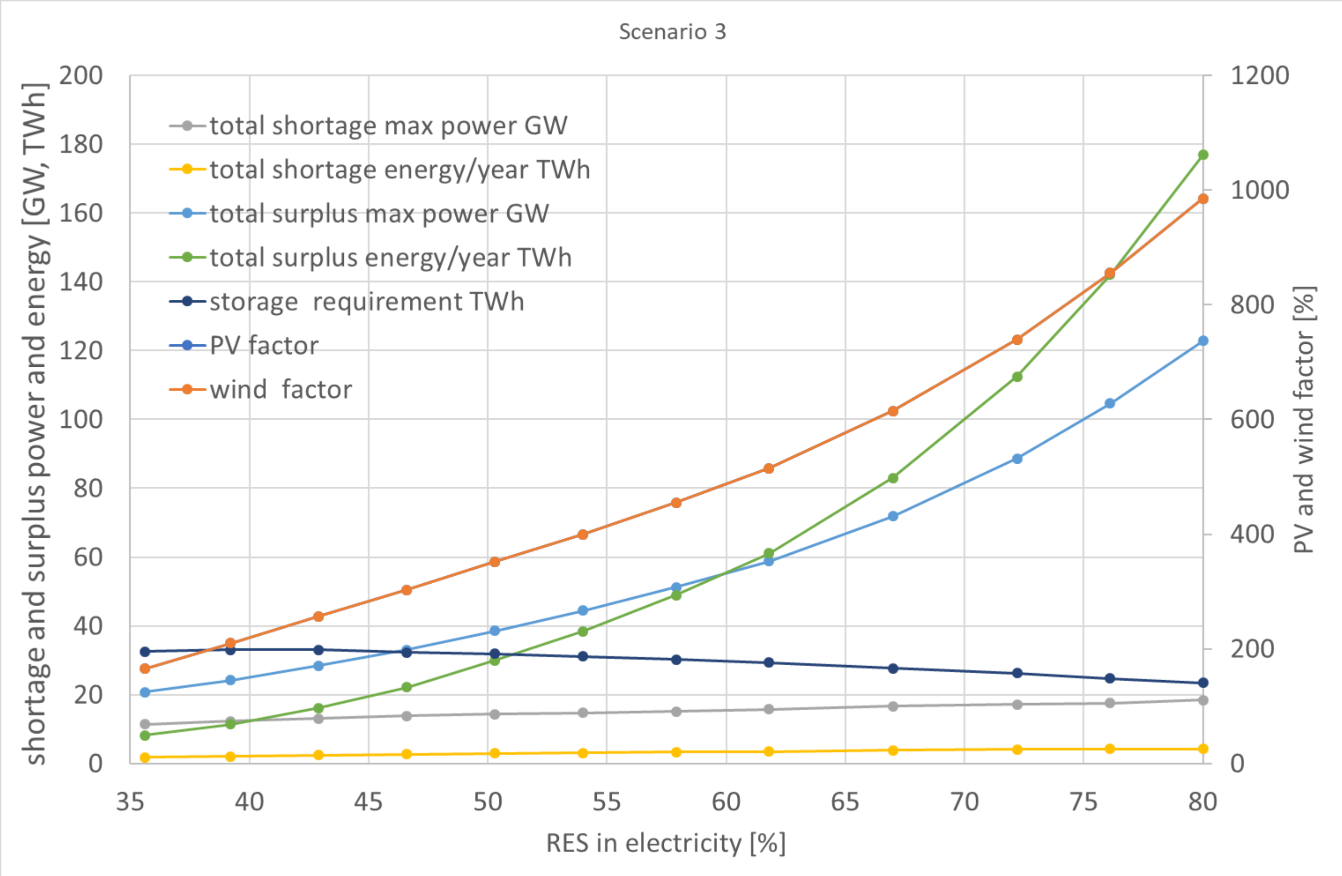

Figure 13: Scenario 3, PV : wind = 1 : 1 of installed power, 25 % EV, storage share 100 %, no disturbance

Scenario 3 is shown in Figure 13. Scenario 3 uses ratio PV : wind = 1 : 1 of installed power, estimates 25 % share in EV, while keeping storage unchanged from current situation. Wind and PV factors have in comparison with scenario 1 increased and so has total surplus energy.

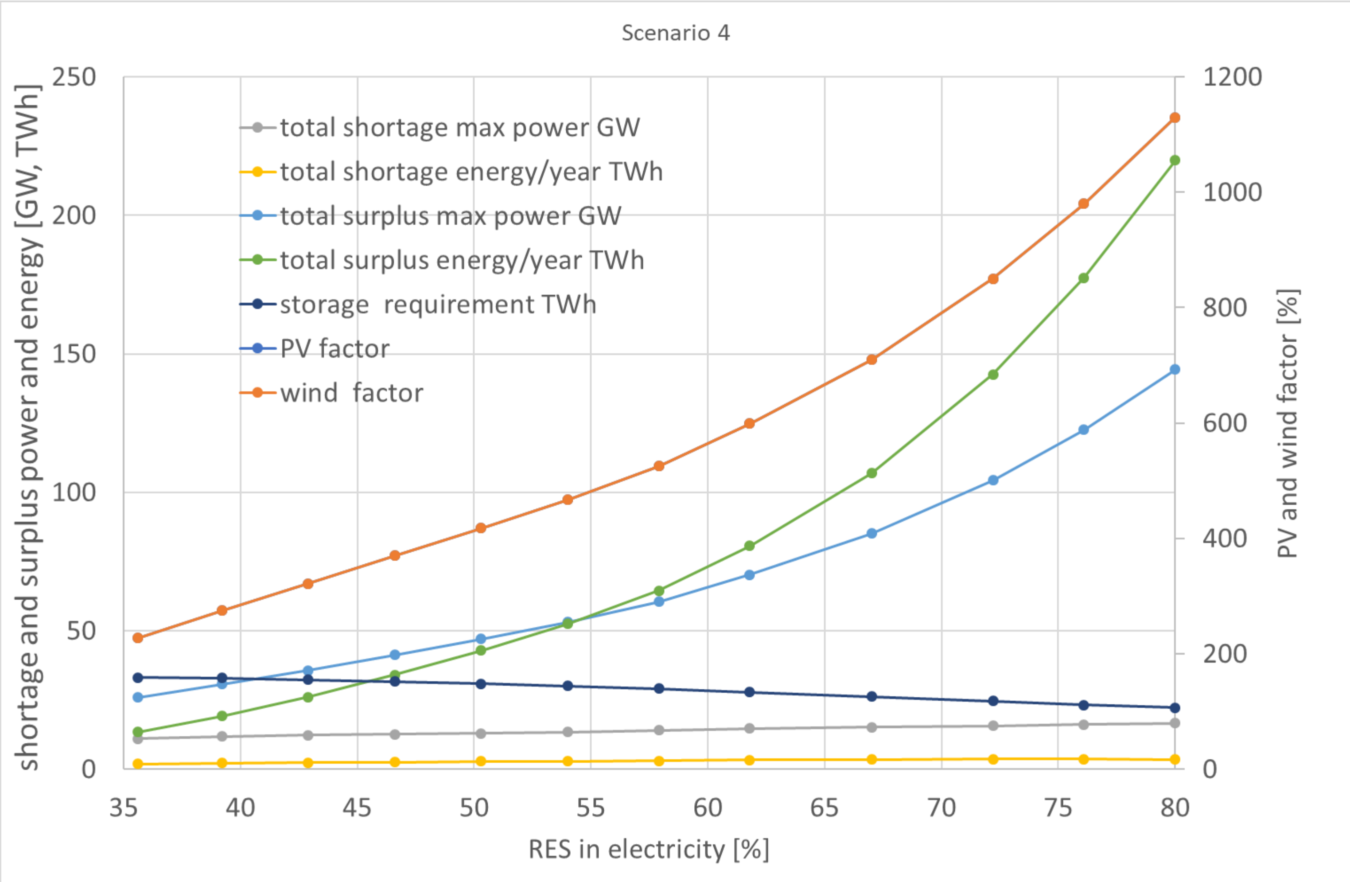

Figure 14: Scenario 4, PV : wind = 1 : 1 of installed power, EV 50%, storage share 100 %, no disturbance

Figure 14 shows influence of EV charging (scenario 4, PV : wind = 1 : 1 of installed power, EV 50%). Direct comparison with scenario 1 shows, that charging of EV increase required installed power, while PV and wind factors increase by around 300 %. Again, requirement for energy storage is low and more than 200 TWh of electric energy must be rejected, as they are surplus that cannot be stored with the currently available electric storage capabilities.

Car batteries can be charged and discharged in many ways and may act as an electric energy storage if well connected to the electric grid. EU should in the future stimulate their use as an electric energy storage. However, we must not neglect the requirement that they must be full to provide for mobility whenever required and enable sustainable society and economy growth.

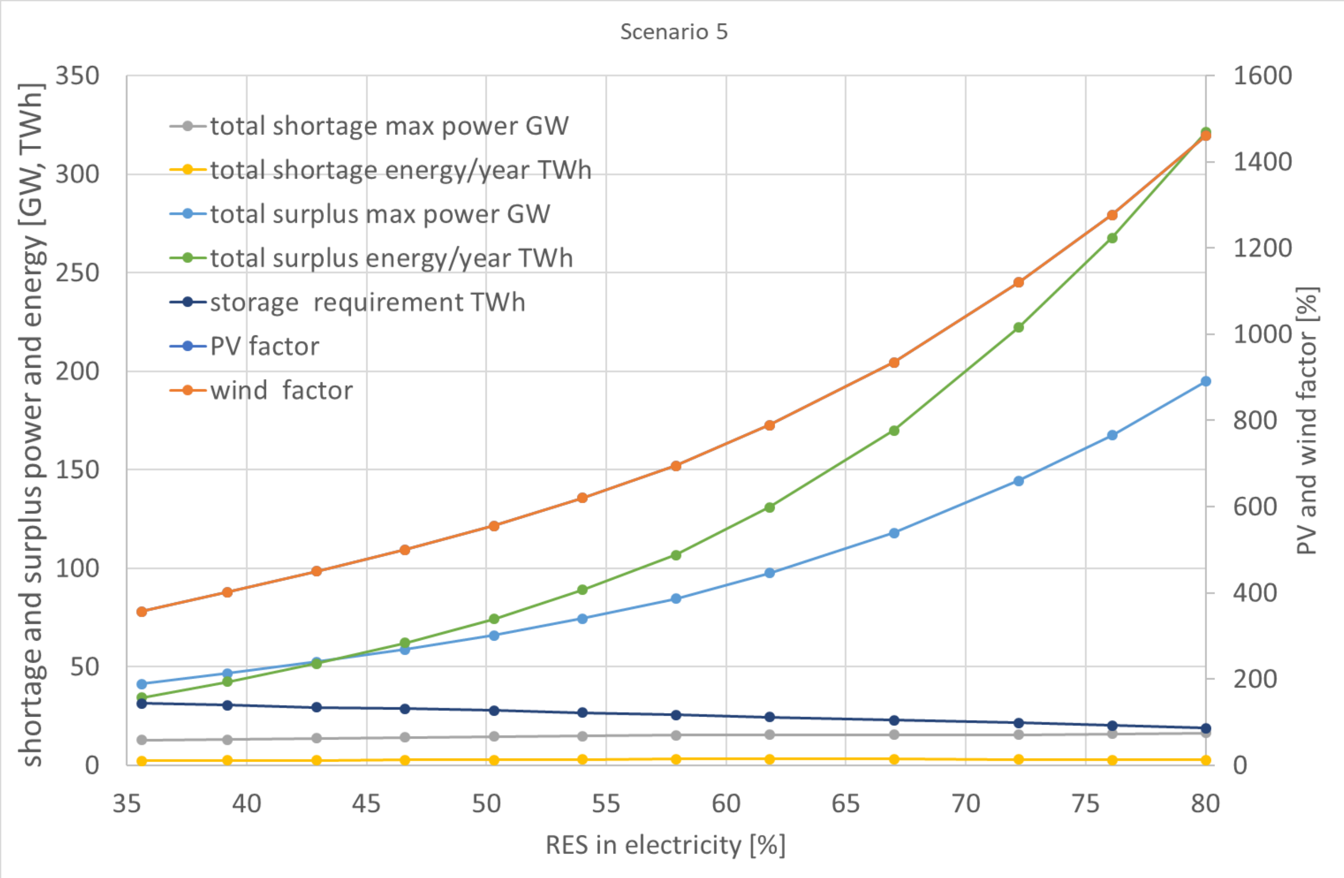

Figure 15: Scenario 5, PV : wind = 1 : 1 of installed power, EV 100%, storage share 100 %, no disturbance

Figure 15 shows situation, where all cars are electric (scenario 5, PV : wind = 1 : 1 of installed power, EV 100%). In comparison with scenarios 1 and 4 with 0 % and 50 % of EV, results show further increase of required installed power of RES sources, reaching over 1400 % of todays installed power. Storage requirement and shortage remain at levels from previous scenarios.

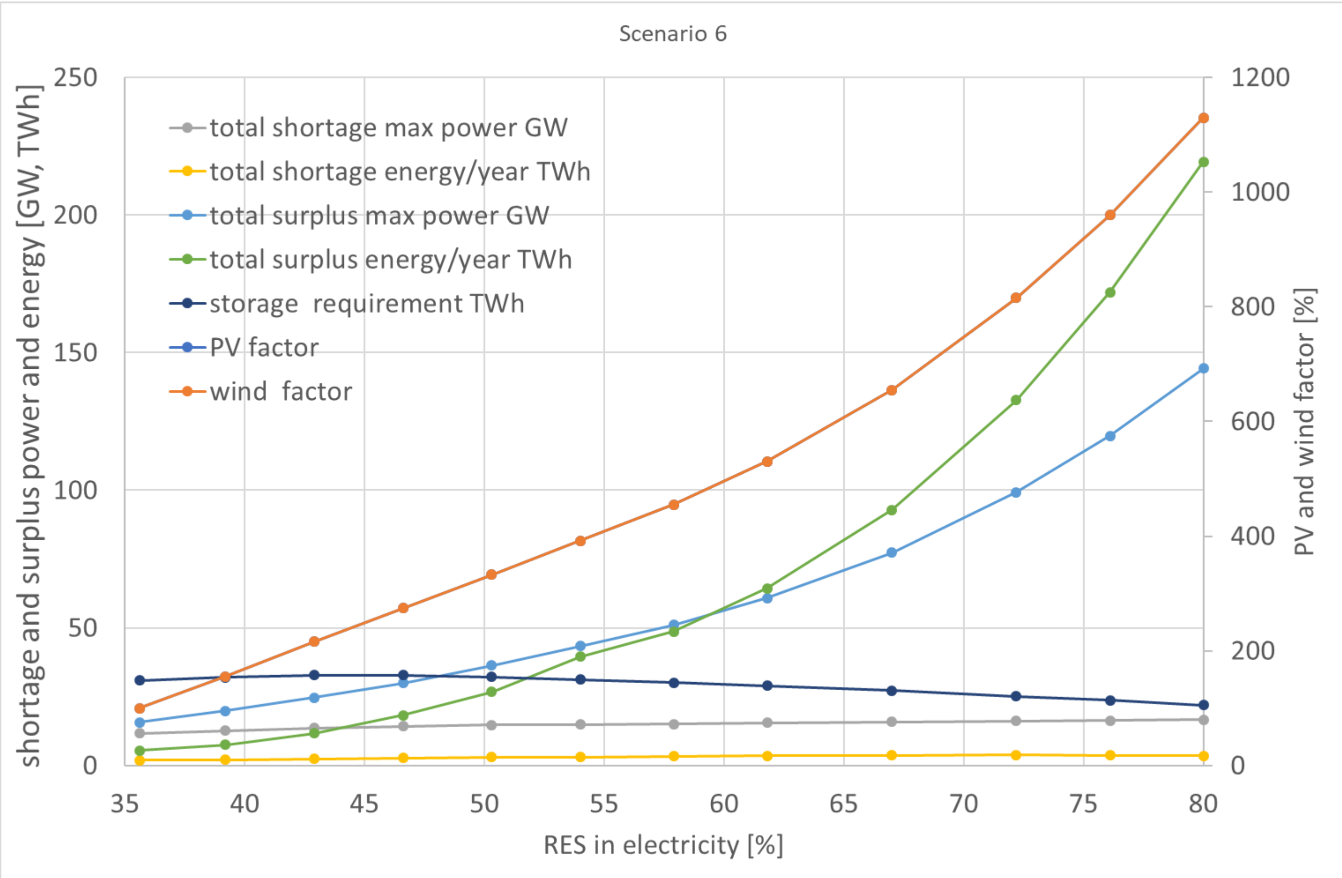

Figure 16: Scenario 6, PV : wind = 1 : 1 of installed power, EV share as shown in Figure 7, storage share 100 %, no disturbance

Scenario 6 (Figure 16) is similar to scenario 1, while it features gradual increase of EV from Figure 7. In comparison with scenario 1 we notice much higher requirement for PV and wind factor. Total surplus energy and maximum power are both much higher in scenario 6.

Scenario can also be compared to scenario 4. In scenario 6 number of EV increases gradually according to Figure 7, while in scenario 4 it is held constant at 50 %. While difference is not high, gradients of PV and wind factors become steeper at around 80 % RES. For high PV scenario, this feature would be even more expressed. At 80 % RES, scenarios 4 and 6 are equal.

Other variables (surplus energy and shortage) do not differ much from previous scenarios.

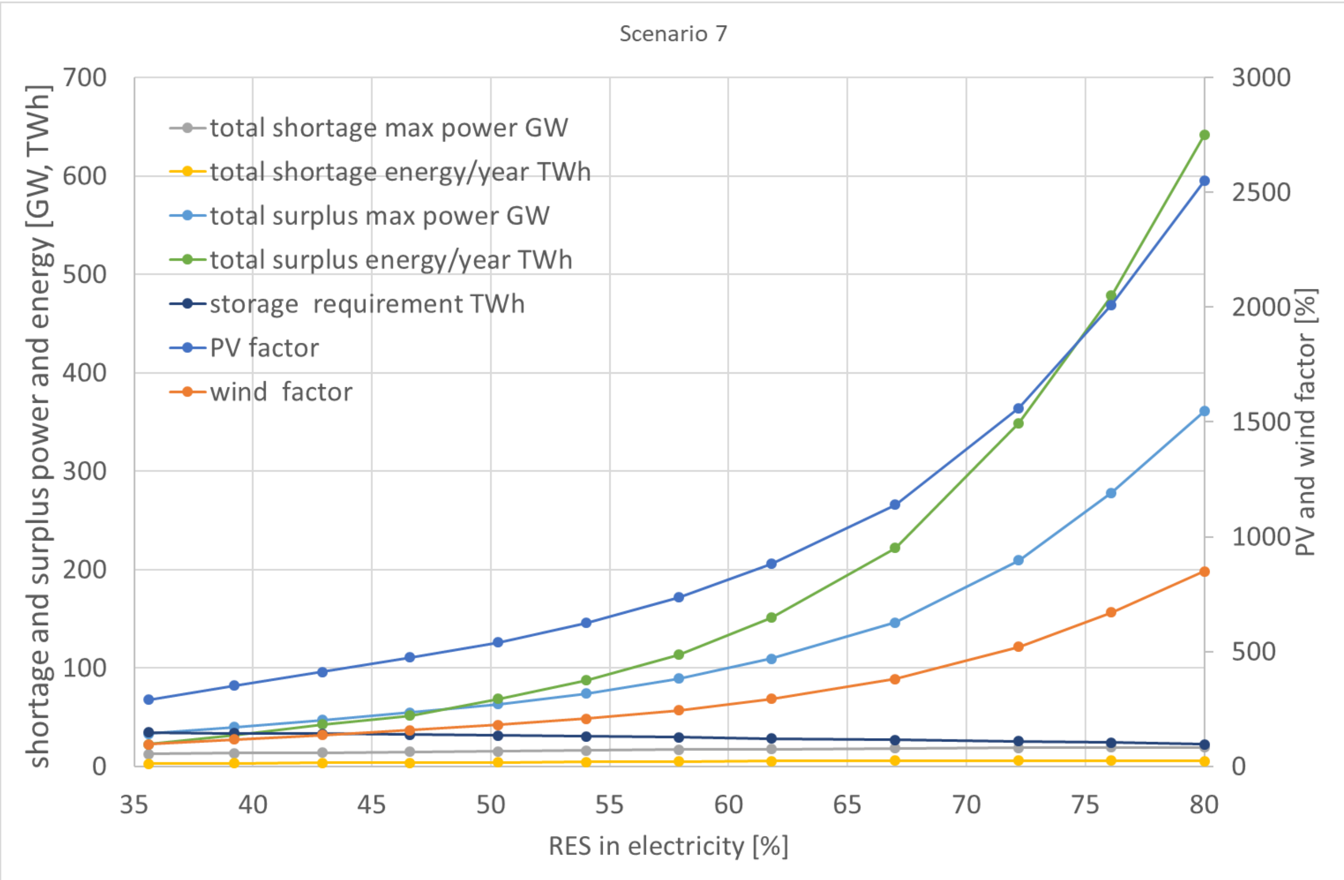

Figure 17: Scenario 7, PV : wind = 3 : 1 of installed power, EV 50%, storage share 100 %, no disturbance

Figure 17 shows scenario 7 with ratio PV : wind = 3 : 1 of installed power and EV 50%. This scenario is very relevant, as it is likely that in the future until 2050 we will reach around 50 % of electric mobility and PV sources will prevail (3 : 1) over wind due to easier installation. Results from scenario 7 shows extremely high requirement for installed power of RES sources, reaching for over 2500 % of currently installed power and almost 600 TWh of rejected electric energy. Such very high amount of rejected electric energy will make PV a very unattractive source of electric energy for investors. Also, current owners of PV power plants will experience a reduction of amount of electric energy, which they will be able to supply and sell to the electric power system operator. As in other scenarios with the same amount of electric energy storage as here, apparent requirement for electric energy storage is low. Maximum storage and generating power are too low to achieve conditions that can reduce amount of rejected power from PV.

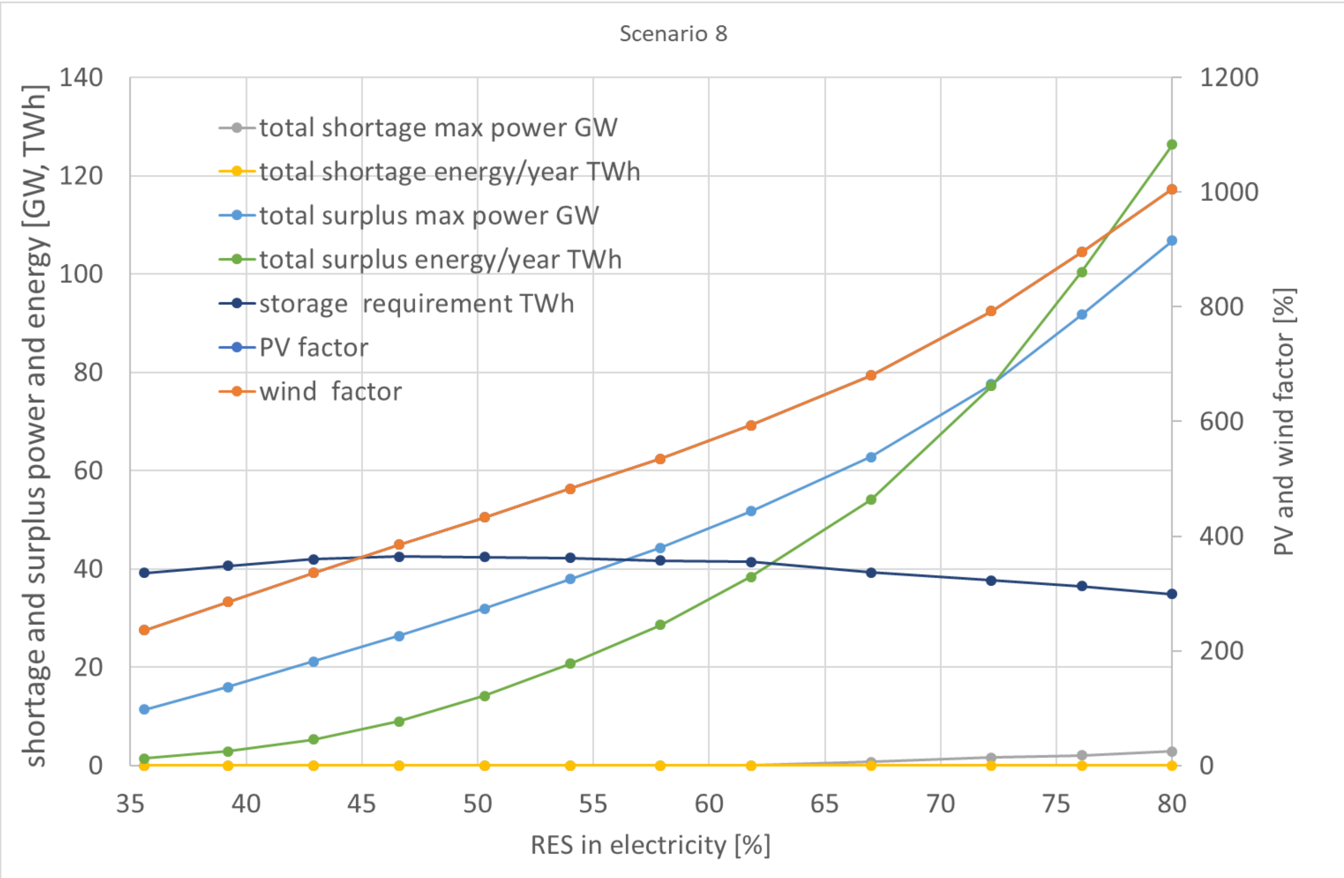

Figure 18: Scenario 8, PV : wind = 1 : 1 of installed power, EV 50%, storage share 200 %, no disturbance

Figure 18 shows scenario 8 with ratio PV : wind = 1 : 1 of installed power, EV 50% and PSH 200 %. Results may be compared with scenario 4, with the same characteristics except that scenario 8 features double electric energy storage capability.

Results from Figure 18 show much improved situation for require installed power for PV and wind sources. Results also show that total surplus energy has decreased much to only slightly more than 100 TWh in for 80 % RES (in comparison with scenario 7 there were more than 600 TWh for 80 % RES). Also, EUSALP would have very limited energy shortage in such scenario. Interesting to note is that in scenario 8 we have peak of requirements for storage at around 50 % RES share in electricity.

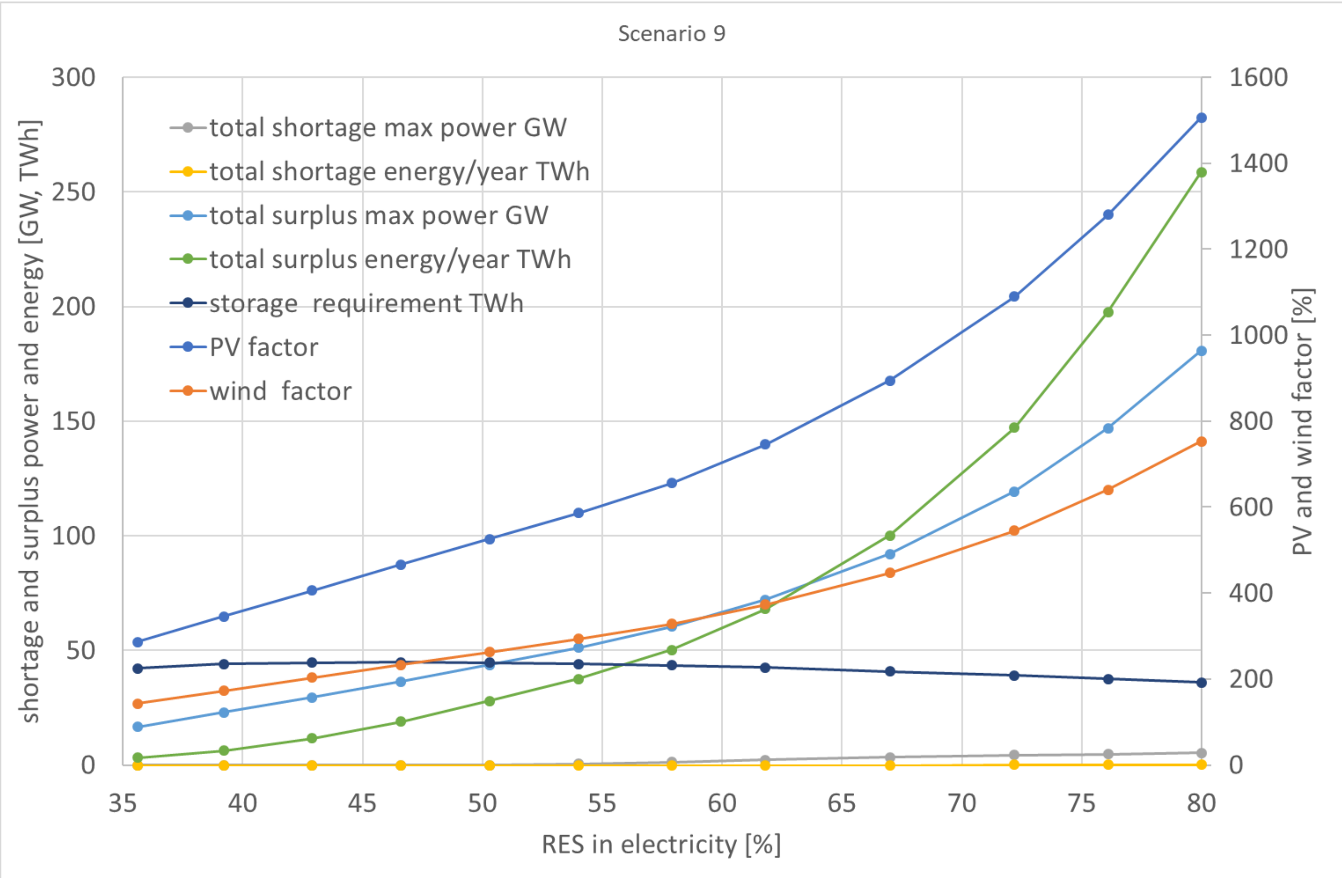

Figure 19: Scenario 9, PV : wind = 2 : 1 of installed power, EV 50%, storage share 200 %, no disturbance

Scenario 9 (Figure 19) shows an intermediate scenario with proposed development in installation power ratio PV : wind = 2 : 1. The scenario 9 falls between scenarios 8 (ratio PV : wind = 1 : 1) and 9 (ratio PV : wind = 3 : 1). Two-fold increase in energy storage, compared to current installed power, helps to decrease PV factor, however total surplus in electric energy production remains very high, being positioned between scenarios 8 and 9.

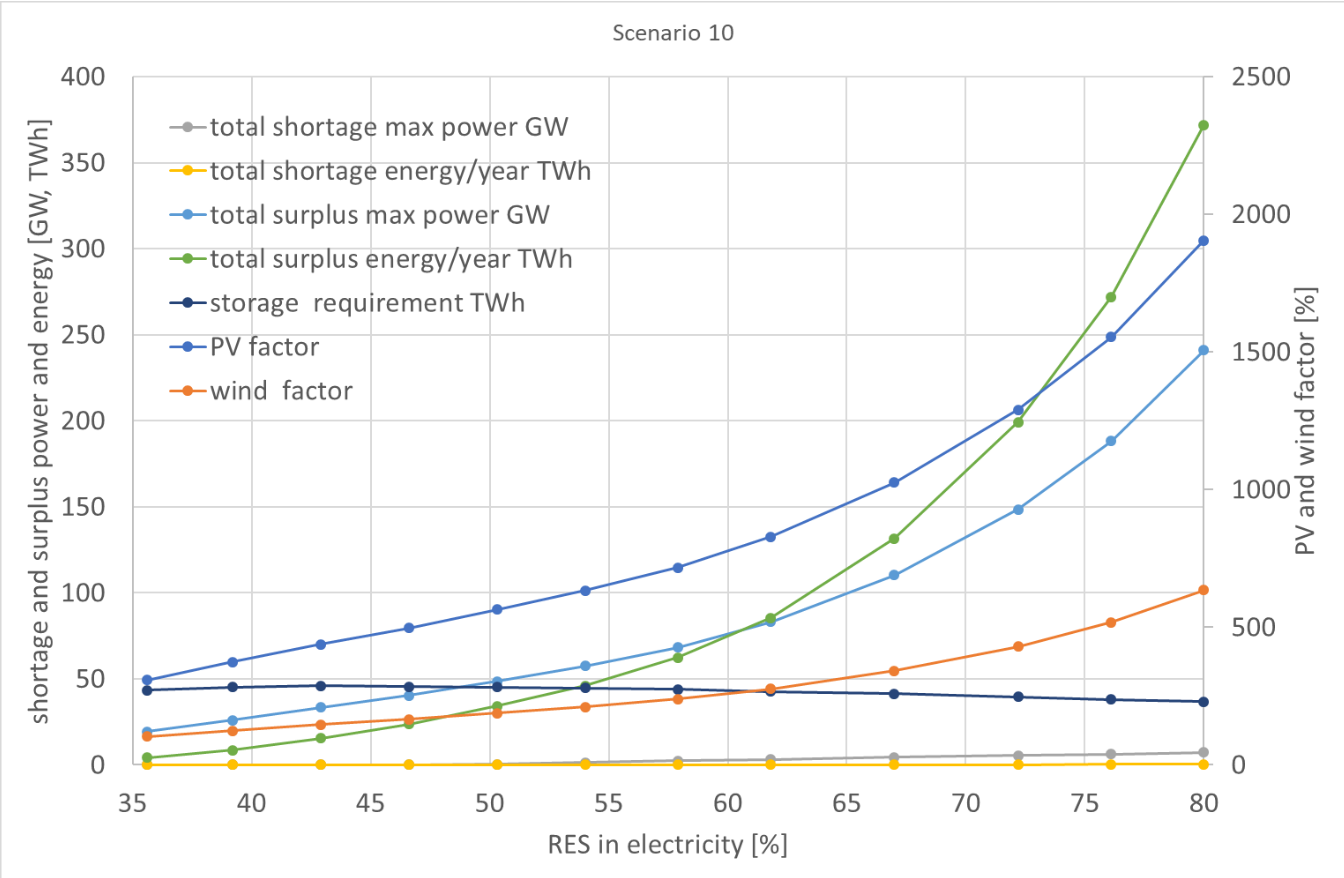

Figure 20: Scenario 10, PV : wind = 3 : 1 of installed power, EV 50%, storage share 200 %, no disturbance

Scenario 10 from Figure 20 is a very probable scenario for future development of electric energy supply in EUSALP. Ratio PV : wind = 3 : 1 of installed power seems logic development of RES market, because PV power plants are relatively easy to install. Despite two-fold increase in energy storage, total surplus in electric energy production remains very high at above 350 TWh for 80 % RES. PV factor for 80 % RES is at more than 1900 %. Also, increase in PV factor is very steep from around 65 %, same being true for total surplus energy. In scenario 9, energy shortage is low due to increased amount of energy storage.

Comparison with similar scenario 7 is interesting. In comparison with scenario 7, scenario 9 features PSH at 200 %. We notice, that in scenario 9 both total surplus energy and PV factor decrease by a large margin (for instance total surplus energy from 641,6 TWh to 371,9 TWh). Increase of PSH storage enables significantly better utilisation of PV and wind power plants.

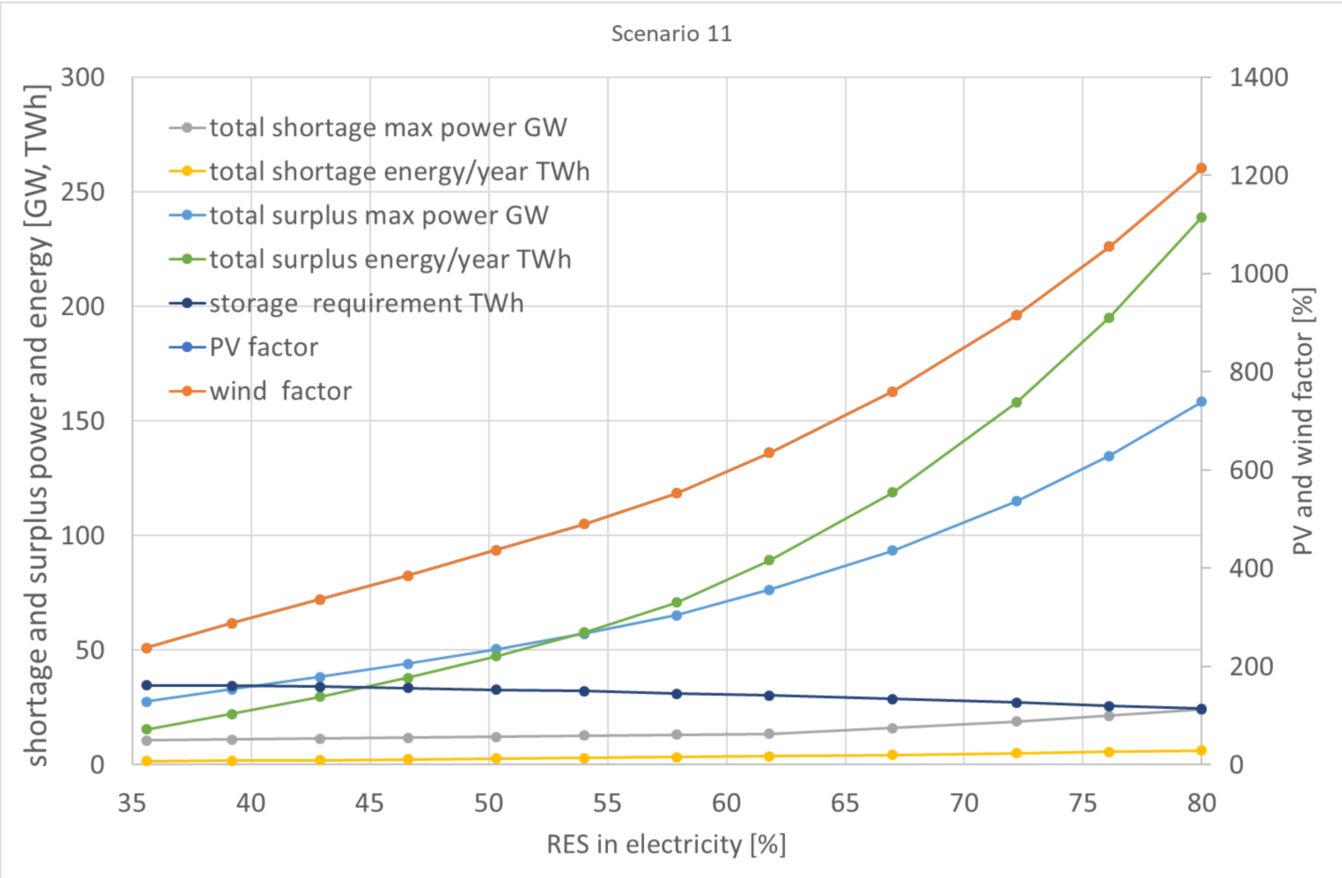

Figure 21: Scenario 11, PV : wind = 1 : 1 of installed power, EV 50%, storage share 100 %, disturbance from 5.-20. March (90 % reduction in wind and PV generation)

Figure 21 shows scenario 11 with a disturbance in production of RES sources. The scenario includes disturbance of reduced production from 5.-20. March. The disturbance features 90 % reduction in both wind and PV generation.

Apart from the disturbance, scenario 10 is the same as scenario 4. PV. In scenario 11 PV and wind factors are higher than in scenario 4. Total surplus energy is also higher. Interestingly, total shortage does not increase significantly.

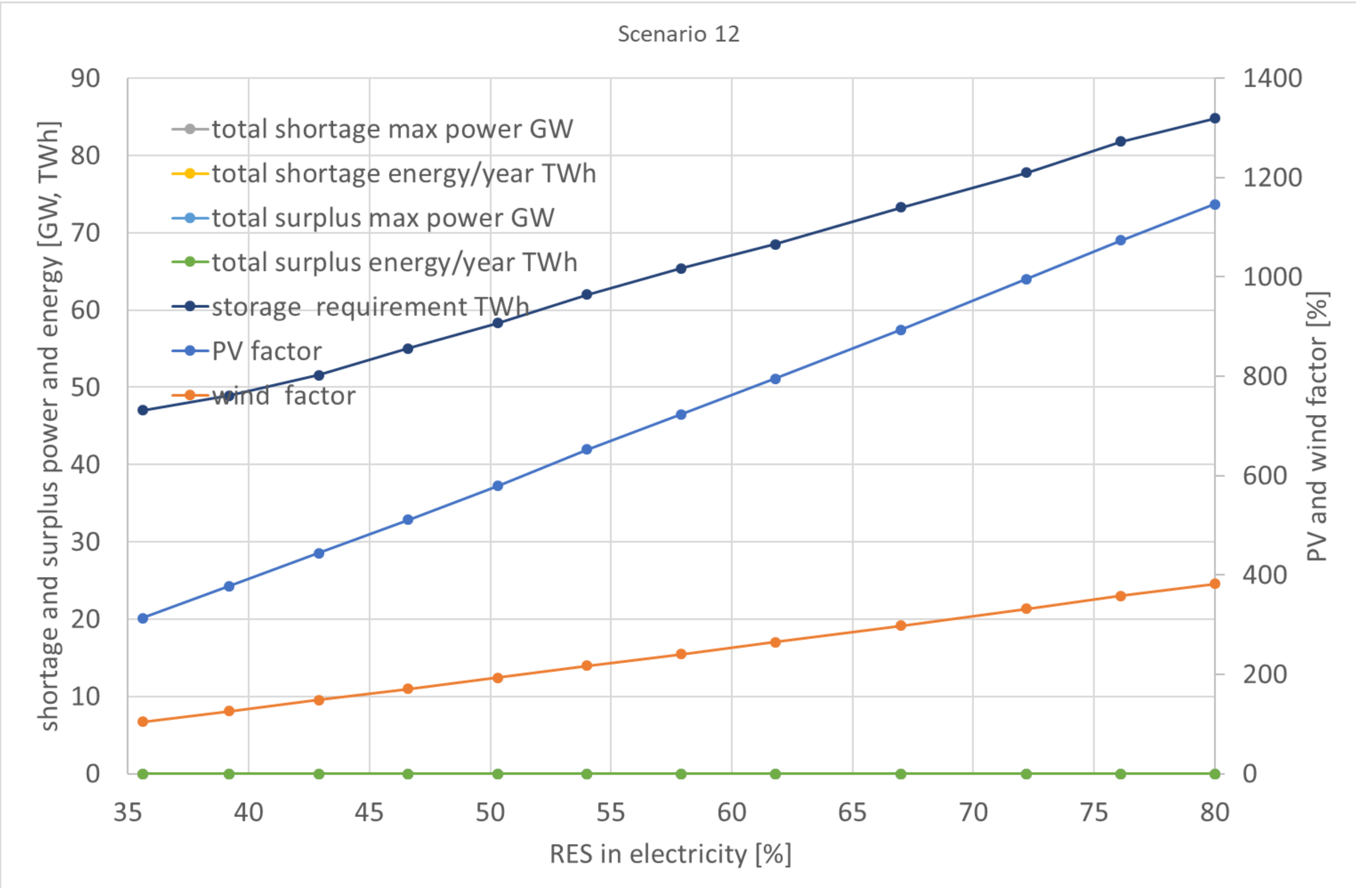

Figure 22: Scenario 12, PV : wind = 3 : 1 of installed power, EV 50 %, storage share 1000 %, no disturbance

Figure 22 shows scenario 12, where amount of storage was greatly increased, PV = 3x wind, EV = 50% and PSH = 1000 %. We notice, that storage requirement increases with increase of RES up to over 80 TWh. No shortage and no surplus energy were recorded, meaning that all RES electric energy production was stored and later used again when required. No surplus electric energy from PV and wind sources enables investors to sell all produced electric energy, further enabling reasonable prices for producers and users of electric energy.

PV and wind factors increase almost linearly with RES share and with years. This gives EU and EUSALP opportunity to easier adapt future requirements as in comparison with exponentially growing PV and wind factors.

Conclusions for section 3:

- low installed power of storage power plants provide for apparent low requirement for storage,
- scenarios with high share of PV in RES electric energy production require excessive installed power of PV and massive surplus of generation, making PV less interesting for investors
- with increasing RES share and high share of PV production, the requirement for electric energy storage will increase
- high energy storage provides for much improved usage of PV and wind electric energy generation.

4. ENERGY STORAGE

In the previous chapter we have shown, that future high RES scenarios will require energy storage to limit amount of surplus energy from RES, which is generated during inconvenient times of the day. In the following we will review energy storage options. From the point of view of the electric power system, this is not only a matter of economic feasibility but of power supply reliability. This problem will gain more and more importance as the amount of non-dispatchable energies increase, as it is foreseen for the future until 2050 [6].

Energy storage in Europe and in the EUSALP region has long history and is widespread. As in other parts of the world, EU is developing ideas for sustainable and efficient energy storage for stationary and mobile applications. We are confident, that energy storage in the EU is lacking strategic support for research and development. This has resulted in delay in research of some of the energy storage technologies.

The following recognized storage technologies are available:

- electrochemical storage,
- chemical storage,
- thermal storage,
- electrical superconducting magnetic energy storage,
- compressed air storage,
- pumped storage hydro and
- kinetic energy storage.

In the following we will review three most promising technologies: electrochemical, chemical and pumped hydro storage.

4.1. Electrochemical battery storage

Electrochemical battery storage is well known and widespread battery storage. Batteries are built from individual electrochemical cells. The electrochemical cell drives a non-spontaneous redox reaction through the application of electrical energy. When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell electrodes supply electrons (oxidation) while ions near the cell other electrode accepts electrons (reduction), to complete the process. The process is reversed to charge the battery.

Each electrochemical cell within the battery has from around 1 - 4 V voltage. Individual electrochemical cells are then connected in series to achieve higher voltages. Batteries feature promising power densities and they have good round cycle efficiencies, ranging from around 70 - 95 %.

The electrochemical battery storage is a mature technology for mobile applications like mobile phones, cameras etc. Electric energy storage required for mobile applications is low in comparison with requirements of electric power system. In Europe, we use around 17,3 kWh of energy [15] per day in 2015. In 2015, that was almost without electro mobility. **Every average EU citizen daily needs the electric energy of around 400 fully charged average laptop batteries.**

For stationary applications of energy storage, electrochemical battery storage can no longer be considered mature. As an example, Li ion battery technology can be called mature in the sense that it is already used widely in a spectrum of applications and yet it is immature in the sense that improved performance is demanded for other new applications, such as those in electricity grids [6]. Even today's most powerful batteries have energy densities from 10 - 100 times lower than hydrocarbon fuels.

Electrochemical electric energy storage on a grid level will likely become one of the key storage technological enabling transition from the current conventional electricity generation in nuclear, coal and gas fired power plants with fast rotating turbines to future RES driven generation (e.g., wind and photovoltaic) coupled with more “intelligent” management of the energy in the form of smart grids, peer to peer trading and/or "demand side management". The role of electrochemical storage will be likely limited to shortest time intervals among all storage methods for primary and to a limited extent secondary reserve power.

4.1.1. Hornsdale storage

We will discuss Hornsdale electrochemical battery storage (Figure 23) in Australia as a representative example of electrochemical electric energy storage. After a series of regional blackouts that appeared in south Australia in September 2016 and February 2017, the grid urgently required stable operation. It was then decided to build the world's largest battery for grid level electric energy storage. The Hornsdale power reserve battery was built by company Tesla. It is located near a wind farm and it is the largest lithium ion battery in the world. It provides 129 MWh of storage capacity, arranged as a grid of scalable connection of battery power packs. Hornsdale battery pack size is 1308 x 822 x 2185 mm each, with capacity 0,158 MWh per pack, with entire installation comprising of 816 packs [22, 23]. It is capable of discharging at maximum power 100 MW, which is by contract divided into two parts. The first part is contracted by the government and can discharge at power 70 MW for 10 minutes and is required to prevent blackouts. The

rest of the battery can discharge for 3 hours at power 30 MW and is used by French company Neoen for load management to store energy when prices are low and sell it when demand is high. Both values are available under the condition that the battery is fully charged.

Figure 23: Hornsdale battery storage, artists impression. [23]

The Hornsdale battery storage is huge in size and complexity, and we should compare it with existing hydro pump storage power plants. Among them, for instance relatively medium sized 185 MW / 180 MW ČHE Avče pump storage hydro power plant in Slovenia, intended for daily operation and storage, can store 2 million m^3 of water and supply 180 MW of power for 15 hours. ČHE Avče has storage capacity of 2700 MWh, around 21 times more than Hornsdale power reserve battery. However, response times of Hornsdale battery storage are exceptionally short, being in the miliseconds range, offering valuable advantage in relation to PSH like above mentioned ČHE Avče pump storage hydro power plant.

Every fully charged Hornsdale power reserve battery pack is enough for daily energy requirements of 9 average EU citizens. The entire Hornsdale power reserve battery storage can supply electric energy for 7400 average EU citizens.

We may safely assume, that prices of battery storage will continue to decrease, and battery storage will emerge as a viable option in locations, where other energy storage solutions are not feasible, as is the case in flat and dry south Australia. Since around year 1970, the lithium batteries are the most advanced type of electric energy storage and large increase of production will seriously deplete available lithium ore resources. However, various sources do not agree whether existing lithium reserves are limiting or not [14 and 25].

4.1.2. Future development for electrochemical battery storage

Before electrochemical battery storage can be widely used in stationary applications, costs, energy density, power, charging power and degradation issues should be improved. For instance, according to [6], targets for energy cost (until 2030) for installation should be below 200 EUR/kwh, power cost < 20 EUR / kWh, < 0.10 EUR/kWh/cycle and lifetime > 5000 cycles for development of existing types of batteries. Safety of lithium batteries should also be improved together with extending the temperature interval of operation.

Development of batteries for market deployment in the second half of 2020 - 2030 period will focus on completely novel materials and electrochemical systems for electrochemical cell voltages up to 5 V, among them Mg, F - ion, Cl - ion, metal - air systems etc. Electrochemical capacitors may also be used in the future. Designs with less toxic electrolytes are preferable.

4.1.3. Batteries in cars

Every electric vehicle needs a charged battery. Charging EV batteries is limited by available charging time and location. Thus we estimate, that without exceptionally well developed charging infrastructure, batteries in EVs can't be a comprehensive solution to electric grid stability. Some EU smart grid scenarios emphasize battery storage in EVs as an important part of grid stability with electrical vehicles batteries on board vehicles as a balancing component in the grid. The envisaged energy flow will be according to such scenarios in both ways, from the grid to the EV battery and back. Current batteries have maximum power and energy, that is too low to efficiently perform all driving tasks (and losses related to driving) and at the same time act as a stationary battery storage. Also, the role of EV batteries in smart grids depends on capabilities of smart grids and on warranty EV manufacturers will provide for such usage.

Thus, we see a limited potential for the use of batteries in EVs for use as the electric energy storage in electric power systems.

4.2. Chemical storage

Chemical energy storage is transformation of electric energy into chemical energy of chemical compounds. When chemical compounds are formed, they may be used in the same way as primary electric energy sources for electricity generation, in internal combustion engines of vehicles including trucks, or for heating. Among chemical energy storages are:

- power to gas,
- power to liquid,
- biofuels,
- boron, silicon and zinc, etc.

Power to gas is an energy storage method, where electric energy is used for generation of gaseous fuels like hydrogen or methane. For hydrogen gas generation, all production methods use electricity to split water into hydrogen and oxygen by means of electrolysis. This reaction is very well known and has been used for more than 100 years. To further produce methane, the second method is to combine the hydrogen with carbon dioxide and convert the two gases to methane using a methanation reaction. Currently round-trip efficiency of power to gas chemical energy storage is well below 50 % by using combined cycle power plants but can reach up to 60 % for cogeneration power plants [6].

Hydrogen can be stored at cryogenic temperature as liquid, as gas at to 700 bars or in solid state materials e.g. hydrides under low pressure. Hydrogen usage is diverse, it can be efficiently reconverted to electrical energy with harmless water vapour as reaction products. Hydrogen can be pumped into national gas grid up to certain amount or used directly for industrial use or transportation. Other fuels may be used for various applications, either stationary or mobile.

The hydrogen power to gas electrolysis is a technology that has not matured yet, it is currently being upscaled to around MW level. Low- and high-pressure hydrogen storage is on the other hand well developed technology.

Chemical energy storage has energy and volume wise a very large storage potential. This is due to possibility for underground storage and very high energy density. When coupled with suitable gas turbine power plants, this may allow for various electric grid services and even seasonal storage.

In the future, investment costs must be reduced, large scale components (scale-up) must be designed and manufactured, efficiency of hydrolysis at high cell currents must be improved, cost of high-pressure storage reduced, and hydrogen storage materials must be found.

4.3. Pumped storage hydro

The pumped storage hydro (PSH) stores energy in the form of potential energy of water, pumped from a lower reservoir to a higher reservoir. PV and wind generated surplus off-peak electric energy is typically used to run the pumps. During periods of high electrical demand, the stored water is released through water turbines to produce electric power and sold at premium price. PSH is the most efficient, proven and flexible large-scale means of storing energy available today. Reservoir and pumped storage hydro are therefore set to play a key role in enabling countries to meet their ambitious targets to cut greenhouse gas emissions and to build additional clean, renewable energy capacity [6].

Electricity is worldwide produced in hydroelectric power plants in 150 countries; the Asia-Pacific region in 2010 generated 32 % of its electricity from hydropower [13]. China is the largest producer of over 800 TW h in 2012, which represents around 17 % of Chinese domestic electricity consumption [13]. The greatest potential for growth in the production of electricity from hydroelectric power plants is in China, Latin America and Africa.

Production of electricity in hydroelectric power plants is the most commonly used form of renewable energy in EU. In 2017, it accounted for around 10.6 % of total electricity production in EU [12].

The cost of electricity production in hydroelectric power plants is very low, thereby hydropower is cost-effective source of renewable energy. The average cost of electricity in large hydro power plants ranges from 3 cents to 5 cents per kilowatt hour. Hydropower is also a flexible source of electricity production, since the electric power production can be during energy production rapidly increased or decreased, whereby the water power plant operation is changed. However, damming of the stream flow which is required for dammed hydroelectric power plants, may disrupt the water flow of the stream and can alter the local ecosystem. In some cases, construction of dams and reservoirs include displacement of the population. When the hydro power plant is built, it produces no direct waste and has a greatly reduced production of the greenhouse gas carbon dioxide CO_2 compared to fossil fuel power plants.

Operation of PSH has changed with the introductions of RES in electricity. From peak load generation assets operating at maximum power during several hours of the day to provide high value energy, the plants now increasingly operate to provide frequency regulation and therefore need to be operated over wider range of power and with as short as possible reaction time [6].

4.3.1. Technical description of hydraulic power plants

In the turbine machinery the energy conversion is indirect and always takes place through the change of kinetic energy of the fluid. In the turbine the fluid flows from the pressure penstock into the turbine machine and first flows through a cascade of guide vanes (Figure 24). In the cascade of guide vanes flow velocity and with it connected kinetic energy increases at the expense of reduction of pressure or potential energy. At the same time the shape and direction of guide vanes direct the flow in the tangential direction of the runner. However, only tangential velocity can increase, the axial velocity cannot increase due to conservation of the mass flow rate. In the runner, the fluid transfers its kinetic energy to the runner by changing its direction. This decreases the tangential velocity, while again axial velocity does not change much. The flow exits the turbine with reduced energy on the suction side of the turbine.

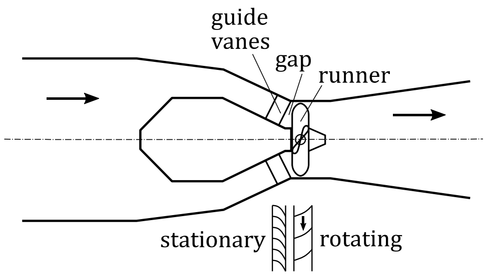

Figure 24: Turbine machinery working principle: axial turbine

The PSH power plants operates as a turbine when electric grid requires electric energy and as a pump when surplus energy is available. As a usual example, the horizontal profile of hydro pump turbine storage power plant Avče is shown in Figure 25.

Water is stored in upper accumulation as a means of potential energy. The water then flows to the turbine through the combination of open channels, closed tunnels, surge chamber and penstock to the turbine. Mechanical end electric part of the turbine starts at the turbine valve in the machinery hall (at the end of penstock), where potential energy of water in upper accumulation has been transformed into pressure. In the spiral casing and guide vanes, pressure energy is further transformed in to tangential velocity, which then acts on the turbine blades. Turbine blades decrease tangential component of velocity, and this momentum is through the shaft transformed in generator to useful electric energy. Water exits turbine through

draft tube, where energy of water is reduced to almost zero. In the pump mode of operation of PSH the water flow direction is opposite than in turbine mode of operation.
Currently all pump turbine storage power plants in Europe are connected to the transmission grid.

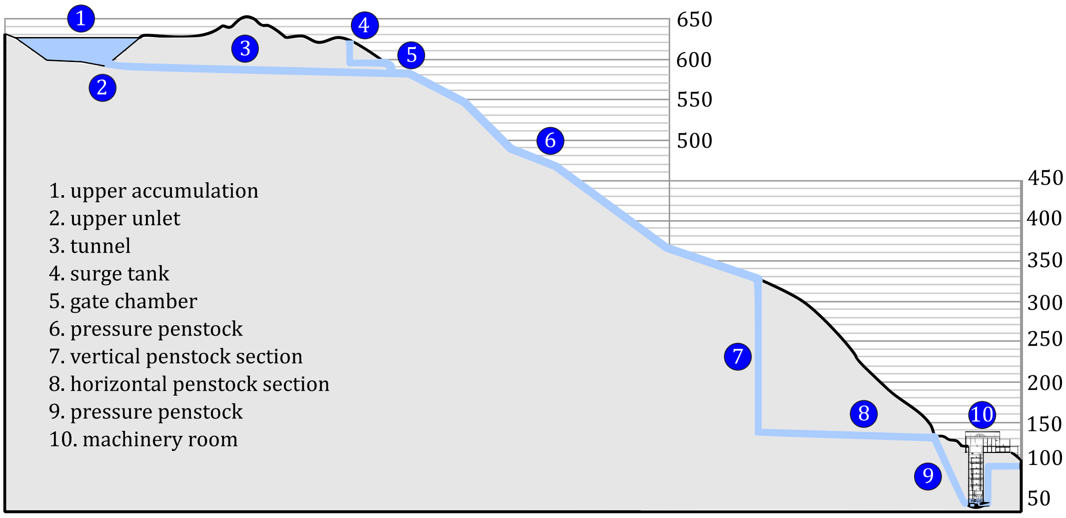

Figure 25: Horizontal profile of hydro pump turbine storage power plant Avče, Slovenia. Machinery hall is in the low/right corner. The vertical 7 and horizontal penstock 8 were built because of steepness of the hill at that location and possibility of landslide in the case of horizontal penstock.

The largest producers of water turbines in the world are Andritz, Voith hydro, Alstom power, General Electric, Mitsubishi, Hitachi, Wasserkraft Volk, Stellba, ČKD, Hydrolink, Turab, Ossberger, FARAB, Gilkes, itd. Some of them have headquarters and manufacturing sites in EUSALP region.
The specific density of energy stored using PSH is low. For usable energy storage very large volumes of upper and lower reservoirs are required. **1 m^3 of water lifted 100 m equals around 277 Wh of energy or less than 2% of current daily use of average EU citizen.**

4.3.2. Future of pumped storage hydro

PSH is already a mature commercial technology and future development aims at improved flexibility, widening the use of PSH, small increase of efficiency and overall improvement of business opportunities.

The requirement for increased flexibility is the most important development criteria for next decade. PSH must be optimised to generate power in generation mode with high efficiency at a very wide interval of volume flow rates. In pumping mode, variable speed technology must allow the regulation of power and volume flow rate. An ever-increasing share of intermittent RES electricity sources will bring requirement for regulation in millisecond time intervals, further strengthening the requirement for variable speed technology. Low head (below 50 m) PSH suffer from the problem of in relative terms fluctuating operating conditions. For this, double regulated Kaplan or bulb turbines are used. Variable speed technology may help to achieve operational stability in pumping mode of operation. Efficient operation of low head PSH is required for their profitable operation.

Additional flexibility of PSH turbines should come from improved hydraulic design. Nowadays PSH operate from around 60 % to 100 % of nominal power. Operation outside this interval is not possible due to increased turbulences and resulting vibrations.

For environmentally friendly operation, truly fish friendly turbines are required. Also, development of standardised mini/micro/nano PSH units for the use in the electric distribution networks will be relevant.

4.4. Which electric energy storage technology is the most promising for EUSALP region?

The most promising electric energy storage technologies are electrochemical and PSH storage. We focus on time interval until 2050. Large electric power producers and electric network operators traditionally prefer reliable solutions, hence market penetration of new technologies in electric energy generation and storage sector is very slow, usually measured in decades. New emerging technologies will require decades to be matured, upscaled and implemented.

Selection of both suitable methods is based on efficiency and availability of both methods, among them is PSH storage already mature technology, while electrochemical storage features one large system in operation. PSH electric energy storage will prevail in EUSALP region because of suitability of EUSALP region for PSH installations but will be supplemented with electrochemical storage for the shortest time intervals.

The methods, that we consider conditionally recommendable are chemical storage (due significantly lower efficiency and absence of large installations), thermal storage, electrical superconducting magnetic energy storage, compressed air storage and kinetic energy storage (all these due to lack of development in recent decades).

Both proposed suitable methods of electric energy storage will be analysed by SWOT analysis in section 5 of this report.

Conclusions for section 4:

- very high time variation in electric energy production by RES exists
- Europe must provide a way to counter large and ever-increasing variation of electric energy production from renewable sources
- shift to electric mobility will add significantly to the requirement for energy storage
- shift to renewable energy production will add significantly to the requirement for energy storage
- battery storage will remain limited due to high cost and environmental issues
- pumped storage hydro will prevail in Alpine region

5. COMPARISON OF DIFFERENT STORAGE TECHNOLOGIES

In the sections 3 a, requirement for increase in storage of electric energy was identified. Increased electric energy storage will improve utilisation of RES in electricity and will reduce surplus electric energy generation. Later in section 4, various electric energy storage technologies were discussed, and electrochemical battery storage and pumped storage hydro (PSH) were identified as the most promising for EUSALP region until 2050. In this section, a SWOT analysis will be performed for these two technologies.

5.1. SWOT analysis

Battery electric energy storage was already briefly introduced in section 4.1 and hydro pump turbine storage in section 4.3. From the comparison of both technologies, we will conclude that hydro pump turbine storage is the most suitable technology for EUSALP alpine region.

A SWOT (strengths, weaknesses, opportunities and threats) analysis is a structured planning method used to evaluate a project or a company (Table 10). The analysis includes inner and outer factors, contributing to the implementation of selected storage technology (lines). Inner factors are those that can be managed within the consortium or are given by the properties of EUSALP region: among them are geographical, engineering, economy, known legislation and management factors. Outer factors are influenced by factors outside the reach of consortium like environmental, societal and trending factors. Both vertical columns include factors, helpful and harmful to reach the goal. Where the intersect, we have:

- **strengths** are properties of the project that provide advantages over other projects, strengths are always internal and helpful to reach the goal,
- **weaknesses** characterize project disadvantages relative to others, they are always internal and harmful to the project,
- **opportunities** are factors, that may provide project's advantage if exploited, they are external and helpful to reach the projects goal and
- **threats** are external factors, harmful to the project.

Usually, weaknesses are related to opportunities, when properly solved.

Strengths, weaknesses, opportunities and threats were evaluated with three levels each. Strengths and opportunities range from + to +++ (maximum identified strength or opportunity), while weaknesses and

threats range from - to --- (maximum identified weakness or threat). Evaluations with up to three + and - levels was introduced in this report solely by authors by careful evaluation of individual properties and do not rely on any literature sources.

The electric energy storage will become increasingly important with years. We envisage, that beside large energy storage, also local energy storage will become relevant and financially justified as the need for energy storage will increase. Therefore, we will in the following discuss global and local energy storage separately for PSH.

Table 10: SWOT analysis as used in this report.

	Helpful to reach the goal	**Harmful to reach the goal**
internal: geo-graphical, engi-neering, econ-omy, legislation and manage-ment	S trengths	W eaknesses
external: environ-ment, society and trends	O pportunities	T hreats

5.2. SWOT analysis of large hydro pump storage power plants

In Table 11, we present the SWOT analysis of large PHS power plants.

Table 11: SWOT analysis of large PSH electric energy storage.

	strengths	weaknesses
internal: geographical, engineering, economy, legislation and management attributes	very favourable geographical conditions for PSH (+++) storage requirements are high and increasing (+++) possibility to sell/buy outside EUSALP region (+++) very high amount of stored energy (+++) very long lifetime (+++) developed technology, very reliable (+++) locally available (+++) no seasonal variability (+++) reliable energy source (+++) cheap operation (+++) predictable operation and maintenance cost (+++) favourable energy received over energy invested (++) no state support required (++) profitable (++) improved water management (++) increased retention of surface and ground waters (++) regulation of rivers (++) high efficiency (++) immediately available (++) source of income during manufacture and construction (++) use of existing infrastructure (reservoirs, penstocks) (+) limited manpower required (M&O) (+) possible long-term storage (+) short response time (+) power plant in cavern - no environmental concern (+)	substantial investment costs (--) need for financing (--) few information available for the specialists – data on social risks not available (--) limited income to local communities from hydro power (--) long return on investment (--) long pre-investment period (--) low specific energetic potential (-) dams and penstocks impact on landscape (-) unable to operate during a long-term draught (-) insufficient and unsatisfactory equipment – investors have too little focus on quality (-) new transmission lines required (-) need of high head (elevation of upper reservoir) (-) long construction time (civil, mechanical) (-)
	opportunities	**threats**
external: environment, society, trends attributes	low CO_2 footprint (+++) sell equipment worldwide, large market (++) sell service worldwide (++) tourism, recreation, attraction and sports (++) brings new investment and funding to local community (++) environmentally acceptable (+) no waste, noise, EMF or pollution (+) sell knowledge worldwide (+) involve local communities to invest their own land (+) local communities' financial benefit (+) dialogue among environmental experts and engineers (+) centralised building permit office (+) prevent immigration of people from undeveloped regions (+) human resources - design, manufacture, service (+) safe (+) development of fishing (+) careful planning may reduce environmental impact (+)	inability of local communities to participate in PSH (--) radically new battery technologies emerge (-) high governmental support to producers in USA, China, etc. (-) climate change (-) worldwide political instability (-) financing - limited interest among investors (globally) (-) technology improvements of other storage technologies (-) limited public (local population) interest (-) possibility of conflicts due to installation in protected areas (-) displacement of people may be required (-) negative impact on the fish population and ecosystems (-) further increase of protected areas size and importance (-) environmental restrictions increase (-) unfavourable legal framework changes (-)

In the following discussion some selected strengths, weaknesses, opportunities and threats will be discussed.

5.2.1. Strengths

PSH energy storage is **mature** and developed technology. PSH energy storage technology is used and produced in Europe for many decades. The first to us known large hydro pump turbine is PSH Walchensee in Germany (Figure 26). It was put in commission in year 1924 and consists of three Pelton turbines for power supply of German railway system and three Francis pump turbines for public and industrial use. PSH have become a mature technology mainly because of **low cost** of operation, long lifetime, cheap operation, predictable maintenance costs etc. Their energy received over energy invested ratio is among the best in energy industry and the most favourable among all RES.

Besides costs, second most important reason for maturing and very successful implementation of PSH is very favourable efficiency, for selected operating points being above 80 % for modern installations with single Francis runner.

PSH power plants require suitable environmental conditions for installations. Upper and lower accumulations are preferably located 100 - 500 m one above the other. Upper accumulations with local topology such that dams may be constructed with low civil engineering costs are preferred. There are plenty of such locations within EUSALP region, some of them enabling also **long-term energy storage**.

Several companies exist in EU and in EUSALP region, capable of manufacturing mechanical, electrical equipment and civil engineering work. Among companies, providing complete PSH solutions are Litostroj, Andritz, Gugler, Voith, ABB, ...). European companies currently suffer from lack of research funding from EU research programs like FP6, FP7 or H2020. Although not being overtaken yet by China or USA, technological advantage was lost in last few decades. PSH power plants will improve in the future in will be faced with new challenges, in the next decade mainly improved availability (also discussed in Chapter 4). EU must invest in research in development of hydropower if we want to keep this important energy business segment competitive and profitable.

Figure 26: Walchensee (Germany, Bavaria) power plant was one of the first PSH power plants.

Besides being used for electricity consumption and generation, PSH can take part in regulation of rivers. **Retention of water** can be achieved during floods by reducing the flow rate at the selected time interval for prevention of peak river water levels and for provision of **ecological flows** during droughts if enough water is available in upper accumulations. When properly used, PSH power plants may contribute to improvement of hydraulic and ecologic situation in rivers.

For comparison with PV, PSH feature very **low seasonal variability** and no daily variability.

5.2.2. Weaknesses

PSH power plants feature few weaknesses. Most of them are related to **investment costs** and **site planning** during pre-investment periods. High investment costs require financing, which may not be readily available without state support. Although operation of PSH is cheap in long term, return on investments periods may be very long. We notice also the trend, that due to limited funding, investors choose equipment of low quality to decrease investment costs. Total costs of operation of such installation over its entire lifetime may however be high.

Social and ecological impacts are related to **dams and transmission lines** construction. Social perception of any kind of HPP today in EU is poor.

5.2.3. Opportunities

CO_2 footprint of PSH power plants is very low within complete life cycle, based on long lifetime and low maintenance costs. Fossil fuels are used for lubricants only. Beside low CO_2 footprint, waste from PSH is almost non-existent.

For transition to RES, entire world will require huge amounts of PSH. A large share of **equipment and services** will be produced (and maintained over the entire lifespan) in factories in EUSALP region, bringing income and social stability to residents. Human resources may be strengthened for some engineering professions, but also for various services and manufacturing capabilities. Currently production of HPP in EUSALP region is abundant, bringing income to EUSALP region, while also maintaining human resources at very high level. We see a growing opportunity to improve this already good situation with the advent of new requirements for operation of PSH, for instance improved availability.

When implemented properly, upper reservoirs of PSH power plants offer huge touristic opportunities. Sight-seeing, hiking, sports, fishing, etc. may bring additional work and revenue to residents. We see the opportunity to revitalize regions, away from large winter tourist centres and large cities. Some of these regions have experienced emigration in last few decades.

Some of weaknesses may be converted into opportunities. Low interest in hydro power including PSH can offer opportunity for local inhabitants to **invest their own land** into PSH projects in a similar way as for wind power plants for instance in Lower Austria. Local community financial benefits may provide crucial to enable building of new PSH units. At the same time, social acceptance of PSH power plants will be improved, providing much necessary boost for large and small installations. These opportunities will be facilitated also by strengthening of **cooperation among environmental experts and engineers**. Future needs for PSH operation will enable higher revenues than today, resulting in careful planning of land use, reducing of environmental impact. Such procedure today is not always possible because of long return of investment and financing constraints.

5.2.4. Threats

Threats are external, and they are from other technologies or from producers of the same technology outside EU. Other countries, especially China invest enormous amounts of funding in HPP, including PSH. Total Chinese governmental investments in hydropower was in 2018 amounted to 8033 million EUR [26].

Beside building of new power plants, Chinese investments into research, design and manufacturing capabilities are huge, posing threat to EU PSH hydro sector. Also, investments into competing technologies may reduce appeal of PSH power plants. Probability for emergence of new and super-efficient batteries technology is very low, Li batteries in various forms are around for more than 40 years, and until now there have been in last 40 years improvements, however not revolutionary ones.

Run of river HPP with dam's impact fish populations in rivers and change ecosystems of rivers. Pressure to improve ecology of HPP operation will likely increase in the future, further reducing already low public interest for building new PSH power plants.

Besides impact on ecosystems, very large PSH power plants may require displacement of people living in locations of upper or lower reservoirs.

The large changes in production, storage and distribution of electric energy and increase of EV in next decades will likely increase the price of electric energy. The addition of RES can reduce its availability. The society must prevent unwanted cases, that poor will have restricted access to electric energy for basic daily needs, while some will be able to fully exploit all benefits of electric energy including electromobility. The storage of energy with PSH at generation and distribution levels will help mitigate induced risks.

Threats in building and operation of PSH will remain small.

5.3. Swot analysis of small hydro pump turbine energy storage

The swot analysis of small hydro pump turbine electric energy storage is shown in Table 12.

Table 12: SWOT analysis of small PSH electric energy storage.

<table>
<tr><th></th><th>strengths</th><th>weaknesses</th></tr>
<tr><td>internal: geographical, engineering, economy, legislation and management attributes</td><td>very favourable geographical conditions for PSH (+++)
storage requirements are high and increasing (+++)
possibility to sell/buy outside EUSALP region (+++)
very long lifetime (+++)
developed technology, very reliable (+++)
locally available (+++)
no seasonal variability (+++)
reliable energy source (+++)
predictable operation and maintenance cost (+++)
benefits from peer to peer electricity trading (+++)

profitable (++)
improved water management (++)
increased retention of surface and ground waters (++)
regulation of rivers (++)
high efficiency (++)
immediately available (++)
source of income during manufacture and construction (++)
cheap operation (++)

high amount of stored energy (+)
favourable energy received over energy invested (+)
limited manpower required (M&O) (+)
possible long-term storage (+)
short response time (+)
power plant small houses - no environmental concern (+)</td><td>substantial investment costs (---)
long return on investment (---)
need for financing (---)

few information available for the specialists – data on social risks not available (--)
long pre-investment period (--)
dams and penstocks impact on landscape (--)

low specific energetic potential (-)
unable to operate during a long-term draught (-)
insufficient and unsatisfactory equipment – investors have too little focus on quality (-)
new transmission lines required (-)
need of high head (elevation of upper reservoir) (-)
long construction time (civil, mechanical) (-)
connection to the national grid (-)
state support required (-)</td></tr>
<tr><th></th><th>opportunities</th><th>threats</th></tr>
<tr><td>external: environment, society, trends attributes</td><td>low CO_2 footprint (+++)
tourism, recreation, attraction and sports (+++)
brings new investment and funding to local community (+++)

sell equipment worldwide, large market (++)
sell service worldwide (++)
involve local communities to invest their own land (++)
local communities' financial benefit (++)

environmentally acceptable (+)
no waste, noise, EMF or pollution (+)
sell knowledge worldwide (+)
dialogue among environmental experts and engineers (+)
centralised building permit office (+)
prevent immigration of people from undeveloped regions (+)
human resources - design, manufacture, service (+)
safe (+)
development of fishing (+)
careful planning may reduce environmental impact (+)</td><td>inability of local communities to participate in PSH (--)

radically new battery technologies emerge (-)
high governmental support to producers in USA, China, etc. (-)
climate change (-)
worldwide political instability (-)
financing - limited interest among investors (globally) (-)
technology improvements of other storage technologies (-)
limited public (local population) interest (-)
possibility of conflicts due to installation in protected areas (-)
displacement of people may be required (-)
negative impact on the fish population and ecosystems (-)
further increase of protected areas size and importance (-)
environmental restrictions increase (-)
unfavourable legal framework changes (-)</td></tr>
</table>

In the following discussion some selected strengths, weaknesses, opportunities and threats will be discussed. We will focus on properties, relevant to small PSH power plants. Small PSH power plants are always inherently connected with local community, so it is required to include local community in planning activities from the very beginning.

5.3.1. Strengths

Most of strengths of small PSH power plants are the same as for the large PSH installations. Small local PSH in addition provide a unique possibility of benefits for peer to peer trading, implemented on a local level of community, village or town. Implementation of small PSH in peer to peer smart grids will reduce loads on distribution networks, which are nearing being overloaded in many communities. The overload is in general a consequence of increased demand in certain periods of time, changing patterns of electric energy use, heating with heat pumps, and electromobility. Reduction of loads on distribution level will reduce costs of energy supply by reducing requirement to upgrade electricity network on distribution level.
Peer to peer electric energy trading is today a novel method of joining producers and user of electric energy on the local level. Several such platforms exist on the market already, among them are platforms Suncontract, Vandebron, EngieNL (Europe) and Power Ledger (USA, Australia, Japan). Although still under development, we list it under strengths. Peer to peer trading is currently driven by economic benefits of service providers. Service providers advertise peer to peer trading as a platform, capable of reducing costs of distribution electric energy. Peer to peer trading platforms introduce a sort of smart grid locally into a distribution network. We see an unused potential of using peer to peer trading for improvement of self-sufficiency on the local level of a village or town. Community embedded within the peer to peer network takes the responsibilities as a supplier. Platform Vandebron for instance aims to become a global supplier with a community-oriented business model.
Peer to peer trading local approach will improve distribution network availability, reducing loads and powers emerging from and during RES peak production and peak use of PHS stored energy.

5.3.2. Weaknesses

Weaknesses of hydro pump storage on a small scale are the same as the weaknesses of large PSH power plants. In general, procedures to build a PSH power plant are too long lasting, and in addition investors have limited influence on how long the municipality planning period will last.

Low specific energy potential will increase costs of energy storage in small PSH power plants per amount of stored MWh. This can be improved by offering financial benefits to PSH in the similar way as supports for RES.

Existing power lines infrastructure on distribution level should be newly built or upgraded, further increasing costs of energy storage on local level.

5.3.3. Opportunities

Until now, there was limited cooperation between local community, investors and producers of HPP and PSH power plants. Local interests are for instance in provision of public lighting during installation and over the entire lifetime for electric energy, operation of rivers, local roads etc. For the municipality it's owned land, existing watercourses and other infrastructure are financial burdens. For the joint PSH energy projects, municipality regards all existing infrastructure as an investment. For local municipalities with abundance of rivers, situation is emphasized.

Several facilities may be designed as multipurpose objects. There were such joint efforts already in the past, but they must be further strengthened. We mention the following good praxis from Soča river (Slovenia)

- multipurpose object on Zadlaščica river for providing potable water to Tolmin town and to produce electric power, located in the wider area of the Triglav National Park,
- on Klavžarica river together with the Ministry of Culture, Idrija museum and local community, the project was initiated involving cultural heritage restoration, MHE Tolminka refurbishment and building of the fish farming facilities, with facilities sharing some of the flow tract facilities.

Local communities are most often interested in limited scale projects like those related to fishing, tourism or flood protection. Examples of more complex projects should also be initiated, forming great opportunities for building of new small PSH power plants while being favourable for local community.

In practice, for local community financial benefits are of the same importance as social and environmental ones. Increasing prices of energy production will likely provide more additional financial benefits to local community. Improved future financial situation can enable the municipality to hire an expert to help promote and provide benefits for their own.

5.3.4. Threats

Large companies, including those in energy production business, should refrain from an aggressive approach towards local communities. Local communities are very vulnerable, while communication with local communities is complex and must be performed with great care. Careful conversation is very important at a very early stage, even before information about intention to build PSH power plants comes into the public. At the very beginning of discussion and cooperation with local communities, expert data are needed about dams or flood waves.

Ministries and other consenting institution still have contradicting opinions about future of PSH. Therefore, coordination between ministries, nature protection institutions, managers, infrastructure planners, etc.) must be improved. Every EUSALP member state or region follows its own procedures. Whenever not already implemented, a possible way forward is to select one governmental institution with responsibility for communication with other governmental institutions and for provision of documentation form all involved governmental institutions.

Acquisition of water rights are difficult on local level.

5.4. Swot analysis of battery electric energy storage

The swot analysis of battery electric energy storage is shown in Table 12 below. In the following discussion some selected strengths, weaknesses, opportunities and threats will be discussed. We will focus on properties of lithium electrochemical cells, inherent to small battery storage, as large-scale battery storage seems less likely now.

5.4.1. Strengths

Battery storage is a very efficient storage method with efficiencies above 95 % for a complete cycle of very slow charge and discharge. A battery storage battery lifetime may be above 10 years, if small charging and discharging currents are used.

When lithium batteries are discharge for less that their rated capacity, their lifetime increases. With current technology and for 20 % of rated capacity being used for every cycle, more than 10.000 cycles may be achieved.

Table 13: SWOT analysis of battery electric energy storage.

	strengths	weaknesses
internal: geographical, engineering, economy, legislation and management attributes	storage requirements are high and increasing (+++) possibility to sell/buy outside EUSALP region (+++) no seasonal variability (+++) benefits from peer to peer electricity trading (+++) very high efficiency for slow discharge (+++) very short response time (+++) source of income during manufacture and construction (++) cheap operation (++) limited manpower required (M&O) (+)	substantial investment costs (---) long return on investment (---) need for financing (---) unfavourable geographical conditions (--) few information available for the specialists – data on social risks not available (--) long pre-investment period (--) battery packs impact on landscape (--) unpredictable operation and maintenance cost (--) state support required (--) poor efficiency and lifetime for high discharge (--) not easily available / high price while in demand for cars (--) medium lifetime (-) low amount of stored energy (-) new transmission lines required (-) connection to the national grid (-) currently not profitable (-) limited source of income during manufacture (-) poor energy received over energy invested (-) long term storage not possible (-) unknown reliability (-) low specific energetic potential (-)
	opportunities	**threats**
external: environment, society, trends attributes	low CO_2 footprint in the installation location (+++) involve local communities to invest their own land (++) local communities' financial benefit (++) environmentally acceptable (+) no pollution on the location of installation (+) dialogue among environmental experts and engineers (+) centralised building permit office (+) careful planning may reduce environmental impact (+) suitable for remote areas with scarce population (+)	worldwide political instability (---) not available in EU - lithium (---) inability of local communities to participate (--) problematic waste when lifetime is exceeded (--) radically new battery technologies emerge (-) financing - limited interest among investors (globally) (-) technology improvements of other storage technologies (-) limited public (local population) interest (-) possibility of conflicts due to installation in protected areas (-) further increase of protected areas size and importance (-) environmental restrictions increase (-) unfavourable legal framework changes (-) safety yet to be conformed (-) lifetime unknown (-)

A very useful feature of electrochemical battery storage is its ability to produce large current and power in the shortest possible time. It can therefore compensate for the RES time fluctuations in production better than PSH. It can therefore be well coupled within the peer to peer networks to provide balancing on peer

to peer level in addition to financial benefits of selling and buying electric energy at the most convenient time.

As with PSH, after installation, limited human and financial resources are required to maintain and operate the electrochemical battery storage.

5.4.2. Weaknesses

When using high charge and discharge currents above 1 C, electrochemical battery storage lifetime is reduced. In the worst-case scenario, this may be to the level of laptop's or mobile phone's battery, which must be replaced every few years. Charging pattern to enable long lifetime is also important. Lithium cells must not be charged or discharged excessively, as in this case the capacity of the cell is significantly reduced in even one irregular charge and discharge cycle, while lifetime is also decreased.

With increasing RES share, requirements for fast and interventions in the electric power system will increase, leading to high charge / discharge currents and deep discharges, decreasing the useful lifetime of lithium electrochemical battery storage.

Requirements for battery cells for electromobility applications will increase until 2050, keeping costs of electrochemical battery storage high.

In comparison with PSH, batteries can store much less energy and are not suitable for more than daily storage requirements.

5.4.3. Opportunities

The most important opportunity for electrochemical battery storage is like in the case of PSH low CO_2 footprint at the installation location. We also see the opportunity for the local community to participate in electrochemical battery storage applications by investing money or land.

Electrochemical battery storage is still accepted as environmentally friendly, although this perception may change for very large installations like Hornsdale battery storage [23].

5.4.4. Threats

EUSALP or Europe does not possess any significant amount of lithium. A large dependence on lithium electrochemical battery storage may expose Europe vulnerable to lithium price fluctuations on the world market. Price fluctuations may arise from large demand, increase of production costs, worldwide instability or similar.

Waste from electrochemical cells may prove a concern with increased electromobility requirements and electric energy storage requirements. Due to a large scale, even state of the art recycling technology may be unfriendly to the environment.

Although lithium batteries are around for more than 40 years and were continuously improved, they are still the most convenient option for electrochemical battery storage of electric energy. New and much better technology may render lithium technology obsolete. We however believe, that probability for such scenario is low.

Conclusions for section 5:

- PSH energy storage is very suitable for EUSALP region
- PSH energy storage has many important advantages over competing technologies like electrochemical battery storage
- local energy storage on small level using PSH is possible and should be exploited in the future
- electrochemical lithium battery storage will be useful for very fast fluctuations in electric energy production and demand

6. CONCLUSIONS AND PROPOSED SOLUTIONS FOR ELECTRIC ENERGY STORAGE IN THE EUSALP REGION

With an ever increasing share of renewable energy sources in electric energy production, electric energy supply will change in the following decades. We have analysed several scenarios of generation and consumption for renewable energy sources shares up to 80 %. Results show, that an increased percentage of renewable energy sources in electricity will result in surplus electric energy, unless enough pump storage hydro or electrochemical battery storage installations will be available to store electric energy at suitable times of the day and of year.

With decrease conventional electric energy production, electric grid stability will be compromised if not enough large pump storage hydro sources will be available to compensate for the variable pattern of electric energy production with renewable energy sources.

High share of renewable energy sources in electric energy generation, steady decline of conventional sources, high requirement for increase of electric energy storage and peer to peer trading will dominate the market in the coming decades.

Renewable energy sources in electric energy generation will increase until at least 2050 [1, 2, 3, 4, 5 and 6]. With increasing renewable energy sources share and intermittent generation of electric energy, we believe that much more large-scale pump storage hydro energy storage will be required, while in addition to large installations small pump storage hydro will emerge, building on local community benefits and benefits from peer to peer trading of electric energy within a local smart grid. The situation is shown in Figure 27. The main benefits of this combinations are:

- little or no surplus RES electric energy,
- lower cost of RES electric energy production,
- stable electric power system,
- low CO_2 footprint of electric energy production including energy required for electromobility even for a high percentage of EV,
- reduction of costs related to selling of electric energy at distribution level,
- forecasting of energy demand (demand side management) and consumption on local distribution level,
- optimisation of energy storage,

- sustainable PSH energy storage installation, available for use for tourism, fishing etc.,
- optimisation of distribution cables load at distribution level,
- independent electric power system on EU level,
- etc.

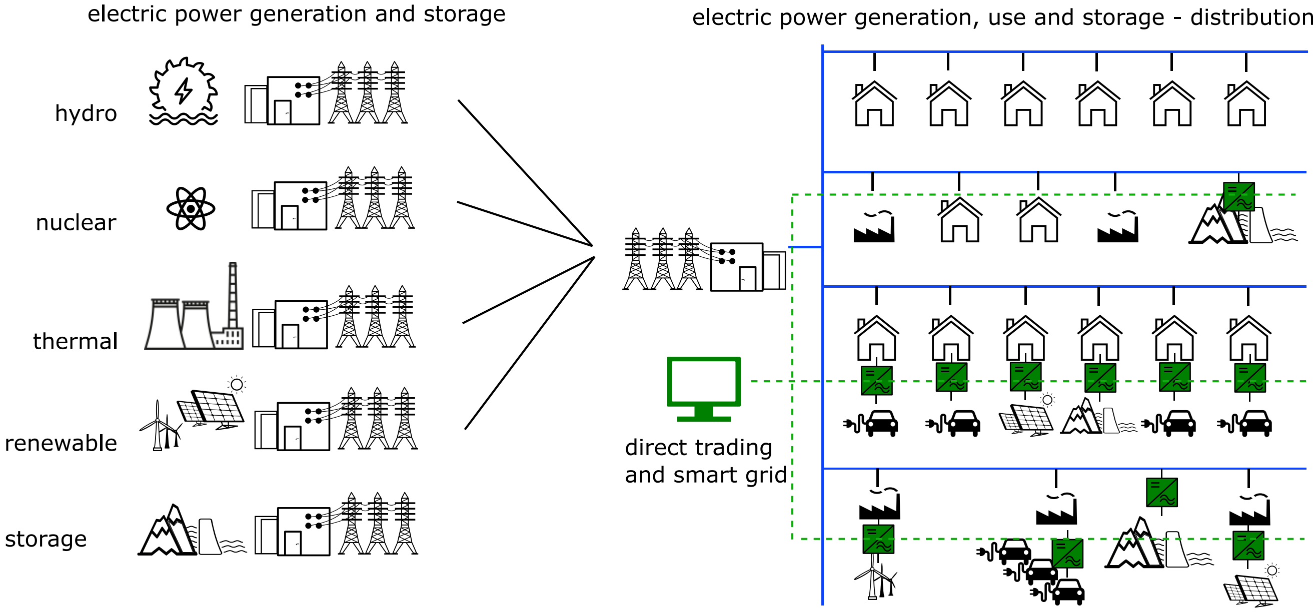

Figure 27: Development of electric energy generation, storage and consumption for the EUSALP region.

Conclusions for section 6:

- electric energy storage will be increasingly necessary due to ever increasing share of renewable electric energy sources
- the PSH in alpine region outperforms other electric energy storage methods by a large margin
- the small hydro pump storage power plants are inviting development
- we propose that governments and their institutions promote research in the field of small hydro pump turbine storage (faster response time, small size) and provide other benefits to maintain capacity for production within EU
- benefits from peer to peer electricity trading is possible for small installations
- procedures to acquire building permit must be simplified
- local community will see clear financial benefit

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