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ROLE OF PUMPED-STORAGE HYDROELECTRIC POWER PLANTS AND LARGE PENETRATION OF ELECTRIC VEHICLES IN INCREASING POWER SYSTEM FLEXIBILITY WITH LARGE SHARE OF RENEWABLE SOURCES

SUMMARY

The European Union's (EU) goals of reducing energy dependence and reducing greenhouse gas emissions (GHG) are to be achieved primarily by increasing production from renewable energy sources (RES). However, due to the features of renewable sources such as unpredictability and lack of availability, it is necessary to increase the flexibility of the systems themselves. In other words, large penetration of RES into the power system requires a substantial increase in the capacity of various energy storage technologies. Pumped storage hydroelectric power plants (HPPs) represent 99% of global installed capacity of energy storage and are widely spread, providing energy storage capacity and transmission grid ancillary benefits in the US and Europe since 1920s, as well as in the rest of the world. Besides, new technologies are considered worldwide, and as one of the most prominent options considered today is the penetration of electric vehicles (EVs) into the power systems. The use of EVs reduces air pollution while connecting them to the smart grids creates the possibility of increasing the flexibility of the power

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system since vehicle batteries could be used as storage but also as sources of electricity.

Using the PLEXOS energy market simulation software, the power system of the Republic of Croatia was modelled in this paper and based on the results of different scenarios, the role of pumped-storage power plants and large penetration of electric vehicles in increasing the power system flexibility with a large share of renewable sources was observed.

Keywords: greenhouse gas emissions, renewable energy sources, electric vehicles, pumped-storage power plants, energy storage technologies, power system flexibility

1 INTRODUCTION

The growing dependence on energy imports, the obligation to reduce GHG emissions, as well as older power plants are just some of the problems that the European energy systems are facing. Challenges such as climate change, security of electricity supply, and competitiveness in energy markets are multilayer and complex and require a profound change in the ways that Europe generates, distributes, and uses energy. Namely, 53.5% of primary energy is imported into the European Union (EU), at a cost of € 1 billion per day, and it is anticipated that for about twenty to thirty years this figure would be around 70%. [1] Moreover, fuel combustion in the transport sector contributes significantly to the total GHG emissions. Namely, transport in the EU member states accounts for 33.1% of total final energy consumption [2] while the share of transport in total GHG emissions is 23% [3]. Joining the EU, Croatia has agreed to fulfil the obligations of the Directive 2009/28/EC, which among other things require that each member state by 2020 achieves a minimum share of renewable energy in the finale energy consumption in transport by 10%. Furthermore, in accordance with the EU framework and other international agreements, Croatia was committed to presenting the Low-Carbon Strategy. The strategy will be a fundamental document in the area of climate change mitigation, but also the roofing economic, development and environmental strategy. The goals of the strategy are based on the European Union's policy on the low-carbon economy, which aims to reduce greenhouse gas emissions by 80-95% by 2050. Accordingly, in October 2014, the European Council adopted the Climate and Energy Framework of 2030, setting the target of reducing CO_2 emissions by 40% by 2030, increasing the share of renewable energy sources (RES) by 27% and the indicative target of 27% reduction in energy consumption. The goals of reducing greenhouse gas emissions by 2030 and 2050 will be implemented in the Republic of Croatia within the framework of the political framework adopted by the European Union.

In order to achieve the set goals it is necessary to change the way in which electricity is produced, distributed and consumed. Namely, modern power systems, mostly built in the 20th century, have been developed in such a way that large generators inject electric power thru transformers into a high voltage power grid, and this power is then transported by a transmission system, very often at long distance. At the end of the transmission system, through a series of distribution transformers, the transported power is directed to medium and low voltage network and to the final consumers. However, the idea of connecting production units to the distribution network has become more and more present and these sources are mainly renewable energy resources since environmental impact is one of the most important factors while considering the connection of new production facilities to the power grid. While RES contribute to reducing environmental impact and increasing self-sustainability of national energy systems, it is important to point out that the increased construction of such sources affects many aspects of the power system such as power generation, frequency control, voltage control and reserve maintenance. In other words, due to the large fluctuations in natural water inflow and intermittent electricity generation of renewable sources, the power systems must provide substantial reserves in conventional sources or significant capacity of electricity storage. This leads to an increase in the price of electricity as well as the costs of the whole power system and limits further development to a greater integration of renewable sources. Electric vehicles and pumped-storage HPPs provide the possibility of storing electricity which opens new possibilities for the integration of RES into the grid.

2 RENEWABLE ENERGY SOURCES

Renewable energy is energy that is collected from renewable resources, also referred to as unconventional sources, which are naturally replenished on a human timescale, such as sunlight, wind, tides, waves, geothermal heat, biomass and biogas. Although renewable resources have significantly lower energy value compared to the fossil fuels, as a result of which their power plants have smaller installed capacity, are geographically more distributed, and are mainly connected to the distribution network, such production units considerably increase the ability to meet the requirements for reducing GHG emissions in accordance with national and international goals and agreements. Unlike conventional energy sources, renewable sources are impossible to exhaust over the time. However, it is possible to completely exhaust their potentials, therefore a careful and long-term planning of production capacities and location of their construction is required. The most significant feature of RES is the possibility of diversified applications. Further, RES have enormous potential, although some more than other considering that production from small hydroelectric power plants depends on natural water inflow and location or that the geothermal energy cannot be fully exploited since the technologies available are not sufficiently developed yet. Also, for most unconventional sources, there is no energy consumption when it comes to obtaining the original form nor is the energy consumed for the transport of the original form because transport is usually impossible. The undesirable general properties of unconventional sources are low surface density, partly inability of transport and storage, and mostly usage in its original form, high oscillation of the natural inflow, small annual usage of installed capacity, which leads to the necessity of accumulating energy or making reserves in conventional sources. [4]

Fulfilled desirable property	░
Partially fulfilled desirable property	▒
Unfulfilled desirable property	█

Properties	Desirable state	Small hydro power plants	Collector thermal use of solar radiation	Photovoltaic Use of solar radiation	Wind	Using internal heat of the environment with a heat pump	Biomass and waste	Geothermal energy
Potenial	big	█	░	░	░	░	▒	█
Renewability	yes	░	░	░	░	░	░	░
Possibility of transport in natural form	exists	█	█	█	█	█	░	█
Possibility of storage in natural form	exists	█	█	█	█	█	░	█
Oscillating natural inflow	small	█	█	█	█	░	█	░
The cost of obtaining the natural form	Doesn't exist	░	░	░	░	█	█	░
Occupation of space at the site of transf.	small	░	▒	█	▒	░	░	░
Emissions at the place of transformation	Doesn't exist	░	░	░	▒	░	█	░
CO$_2$ neutrality, cumulative	yes	░	░	█	░	░	░	░
Efficiency of the transformation process	high	░	░	█	▒	░	▒	█
Duration of capacity utilization	high	█	█	█	█	░	░	░
Reserve or accumulation	Not necessary	█	█	█	█	░	░	░
Possibility of cogeneration	possible	█	█	█	█	█	░	░
Possible diversification	yes	░	░	░	░	░	░	░

2.1 Costs of RES integration

RES (wind and Sun) represent three unique problems that lead to a higher costs of their integration in the power system:

- Variability of energy resources i.e. output power of wind and solar power plants depends on the weather conditions and cannot be controlled in the way that it is done with conventional power plants.
- Unpredictability of production for shorter periods. Therefore, every deviation between the planned production and the actual production has to be balanced in the short term, which leads to the need of maintaining reserves in the power system.
- RES cannot be transported, with the common occurrence that suitable construction locations for RES aren't located on or near the sites of high energy demand.

According to [5] costs of RES are divided into groups:

- Direct costs
- System costs
- Macroeconomic impact

Direct costs represent levelized cost of electricity (LCOE[1]) i.e. they consist of the costs of construction and financing costs, fixed operating and maintenance costs (FO&M), variable operating and maintenance costs (VO&M) and fuel costs. System costs represent additional costs incurred by connecting the production unit to the network and consist of balancing costs (balancing energy), network costs (upgrading/construction of the grid, transmission losses, congestions etc.), and integration costs (needed reserve). Macroeconomic impact is related to the effects of GDP and social welfare, the unemployment rate and the distribution of damage or benefits within individual sectors. Analysis at the level of the overall economy is of crucial importance given the significant expansion of RES over the last few years and since the spread of certain technologies can lead to unexpected consequences for other economic entities and sectors.

3 ENERGY STORAGE TECHNOLOGIES

Energy storage will have an important role in enabling the development of Low Carbon power systems, which is one of the main goals of the EU in the near future. Energy storage technologies can provide additional flexibility for the power system, which is needed to better the balance between production and consumption

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[1] LCOE allocates the costs of and energy plant across its useful life, to give an effective price per each unit of energy (kWh). In other words, it's averaging the up-front costs across production over a long period of time.

of electric energy, since we are facing increasing penetration of RES into the grid. Namely, energy storage technologies would support the system in the case of intermittent and relatively unpredictable production from RES. Locally, at the distribution level, their implementation could improve distribution network management, decrease the costs of production, and increase efficiency. In this way, that may facilitate the introduction of RES on the market, accelerate the decarbonisation of power systems, improve the safety and efficiency of transmission and distribution of electricity (reduce unplanned congestions, reduce fluctuation of voltage and frequency etc.), stabilize market prices of electricity while simultaneously ensuring the security of energy supply.

The need for energy storage technologies derives from the basic characteristics of electricity. Namely, the electricity demand varies depending on the time of observation, geographic position, established patterns of electricity consumption etc., and accordingly the price of electricity changes. At peak loads, the price of electricity is higher because more flexible production units, such as gas power plants, have to be engaged, whose production costs are much higher than the base power plants (nuclear power plants). While in off-peak periods, when the electricity demand is lower, according to the law of supply and demand, the price of electricity decreases. This is exactly the opportunity for energy storage owner to profit financially. Namely, from the point of view of the power utility there is a great potential to reduce total production costs by eliminating the more expensive peak production units by storing energy during the night when the electricity price is lower and returning it to the grid over the peak periods the next day. Also, with a high percentage of penetration of wind and PV in some regions, there is excess energy, which is actually cost-free. This surplus could be stored in energy storage technologies such as EVs or pumped storage HPPs and used later on and thus also reduce production costs. On the other hand, from the consumer's point of view, energy storage can lead to a reduction in the electricity costs. Namely, consumers can buy energy at lower prices, store it and use it during the peak load periods. Also, consumers who have battery systems, such as EVs, can charge them during off-peak period and sell the same to power utility or other consumers during peak load period. The fundamental feature of electricity generates another problem for power utilities, which is to maintain a constant and flexible supply of consumers. If the amount of electricity demanded by consumers at a particular moment cannot be met, the quality of electricity is disturbed and in the worst case, this may lead to a disruption of supply. In order to meet changing energy demand, the appropriate amount of electricity should be continually produced, relying thereby on accurate forecasts of demand. However, today it is still impossible to predict accurately the current consumption of electricity, which results in a difference between forecasted and realized consumption. Therefore, some production units are required to participate in voltage (U-Q regulation) and frequency regulation (f-P regulation) in order to maintain the balance between production and consumption at any time. However, RES such as solar panels and wind power plants do not have any of above-mentioned regulation functions. Therefore, it is expected that energy storages will facilitate the mentioned regulations. For a number of years, pumped-storage HPPs have been used to provide auxiliary services, i.e. production of electricity when there is a lack of production from other production units due to different reasons. Furthermore, energy storage technologies are useful in the events of failures in the power system, which can result in a supply disruption, but the consumption can still be satisfied with the energy stored in the energy storage technologies. Portable batteries can also serve as an urgent resource for electrical devices. Power utilities attempt to predict the future congestions in the power grid to avoid overloads, for example by building new transmission lines or by dispatching generators but they cannot be avoided. However, by installing energy storage technologies at appropriate locations, such as transformer stations at the end of heavily loaded lines, it is possible to reduce congestion by storing energy when transmission lines have sufficient capacity to transmit the required energy, and when the lines are unavailable due to congestion, the stored energy is used.

3.1 Pumped-storage hydroelectric power plants

Pumped-storage hydroelectric power plants, with over 168 GW installed capacity worldwide represent 99% of the world's installed energy storage capacity, which also represents 3% of total global electricity production. Conventional pumped-storage contain upper and lower basins between which there is a height difference. The bottom pool is mostly located either on a river waterway or it is a natural lake or sea. Pumped-storage power plants are most often used in terms of energy arbitrage, i.e. during off-peak periods (when the electricity prices are lower) the electricity is used for pumping the water from the lower to the higher water tank, and in periods of higher demand (when the electricity prices are higher) water flows through the turbine, which drives the generator, into the lower tank, and the electricity is produced. The generators in pumped-storage can operate in two modes, both as a pump and as a turbine/generator (usually Francis). Taking into account the losses due to evaporation of accumulated water and losses due to transformation, approximately 70% to 85% of the electricity used to pump the water into the higher tank can be recovered. Typical discharge time ranges from a few hours to a few days. The benefits of this technology are a very long life span and almost unlimited cycle stability, while the main drawbacks are dependence on topographic conditions and large land use. This technology is currently the most profitable in terms of storage large amount of electricity, but investment costs and the presence of problems of a suitable geographic position (the height elevation between water tanks) are critical factors in decisions regarding the building of such production units and storage technology.

There are three pumped-storage hydropower plants in Croatia, Fužine (operating since 1957), Lepenica (1985) and Velebit (1984). However, HPP Velebit is the only large pumped-storage power plant in Croatia with installed capacity of 276/240 MW (turbine/pump), and an annual production of 430 GWh. The HPP Fužine with installed capacity 4.666/4.8 MW (turbine/pump) uses a water drop between the Lokvarsko Lake and artificial Lake Bajer. The small HPP Lepenica with installed power 1.14/1.25 MW is located in the valley of the Lepenica Stream which is the tributary of the artificial Lake Bajer. So far there are no plans for installing new pumped-storage HPP, though they would be an ideal complement to exploiting the full potential of wind and solar power plants that are particularly present on the Adriatic coast. Also, pumped-storage HPP largely fit into the concept of low-carbon strategy, as their work does not produce harmful GHG emissions.

3.2 Electric vehicles (EVs)

Electric vehicles are powered by an electric motor powered by a battery or other power source. The first electric vehicle originates from the 19th century, and was constructed by Scotland inventor Robert Anderson. Due to the advancement of the internal combustion engine during 20th century, the production and development of EVs fell in the second plan. At the beginning of the 21th century the interest in EVs was renewed, primarily due to the tendency of reducing emissions of pollutants associated with environmental protection and sustainable development, and thus the production of EVs is considerably present. Depending on the type of the engine and how the battery is charged, EVs can be divided into:

- Hybrid electric vehicles (HEVs)
- Plug-in hybrid electric vehicles (PHEVs)
- Battery electric vehicles (BEVs)

In this paper, only battery electric vehicles are modeled, therefore the description of this type of EVs is given below. BEVs are fully electric vehicles, meaning they are only powered by electricity and do not have a petrol engine, fuel tank or exhaust pipe. The basic parts of BEV are rechargeable battery, electric motor and engine controller. The electric engine is the central part of BEV, and this is the only type of drive engine in such types of electric vehicles. It turns the electrical energy from the battery into the mechanical and thus drives the vehicle. The motor is controlled by an engine controller, and the engine controller is operated by pushing the accelerator pedal, which has the role of an analogue-to-digital converter, or by pressing the brake (if the EV has a regenerative braking function). [6]

The most widely used battery technology used in BEVs is Lithium Ion. One of the biggest problems that the EV buyers are facing are high battery prices, inability to charge in the households, underdeveloped battery filing, and still a long charging time. Namely, although the market prices of the batteries are in the downward trend, they are still too expensive to increase the competitiveness of the EVs because the current market price of a new battery is about 80.000 $ (about 500-600 $/kWh). In addition, EVs charging equipment alternates the necessary time to charge a fully depleted battery. Level I equipment provides charging through a 120 V alternating-current (AC) plug and requires a dedicated circuit, and it generally refers to the use of a standard household outlet. Depending on the battery technology used in the EV, Level I charging generally takes 8 to 12 hours to completely charge a fully depleted battery. Level II equipment offers charging through a 240 V, AC plug and requires installation of home charging or public charging equipment. Depending on the battery technology used in the vehicle, Level

2 charging generally takes 4 to 6 hours to completely charge a fully depleted battery. Charging time can increase in cold temperatures. Level 2 chargers are commonly found in residential settings, public parking areas, places of employment and commercial settings. Level 3 equipment with CHAdeMO technology, also commonly known as DC fast charging, charges through a 480V, direct-current (DC) plug. Most Level 3 chargers provide an 80% charge in 30 minutes. Cold weather can lengthen the time required to charge. When connected to the grid EV can operate in four different ways. [7] Grid-to-Vehicle (G2V) when the battery of an EV is charged directly from the grid, Grid-to-Vehicle Half (G2V/2) when the battery does not charge but would otherwise be charged, thus EV is helping the system by providing up-regulation, Vehicle-to-grid (V2G) when the battery is discharged, providing the appropriate reserve, and Vehicle-to-Vehicle (V2V) when instead of taking the electricity from the grid, one EV discharges the battery giving the electricity to another connected EV whose battery is then being charged.

4 ELECTRICITY MARKET MODELING SOFTWARE PLEXOS

For the purpose of analysis in this paper, PLEXOS software tool has been used. [8] Modelling in PLEXOS can be carried out using deterministic or stochastic techniques that aim to minimize an objective function to the modelled cost of electricity dispatch and to a number of constraints including availability and operational characteristics of generating plants, licensing environmental limits, fuel costs, and operator/transmission constraints. After entering all the required system parameters, defining scenarios and setting the planning period, PLEXOS launches a program specialized in solving mathematical optimization problems. The simulation of the solution is based on the MIP mathematical programming technique - mixed integer programming. Also, PLEXOS supports the use of several commercially available solvers: *MOSEK, Gurobi, Xpress-MP* and *CPLEX*. With the completion of solving the mathematical problem, PLEXOS prepares the data for preview in the graphical user interface based on the obtained solutions.

PLEXOS is a simulation-optimization tool based on the object model of the electricity market. The object model defines the set of classes and their hierarchy. The class of objects implies a set of rules and definitions pertaining to a particular type of object. During the preparation of input data, the user creates objects representing each element of the model, whether it is a generator, a network, or a market. All supported elements of the power model and the simulation process are defined by different classes of object model. A well-constructed object model provides wide-ranging capabilities and provides a tool suitable for examining the impact of different energy strategies.

PLEXOS provides different possibilities including:

- Capacity expansion planning – optimization of new generation and transmission capacities with decommissioning of the existing power plants

- Modeling production costs
- Forecast of gas and electricity market prices – based on operational constraints on system and market rules
- Planning of gas and water supply infrastructure
- Market analysis
- Analysis of Transmission Restrictions – prediction and control of congestions in transmission system, transmission within security limits (N-x), outrage planning, optimized power flows modeling
- Operational planning and stochastic optimization
- Analysis of the integration of RES – detailed (5 minutes) production and transmission analysis
- Smart grid planning – modeling of smart consumption, analysis of investments
- Management of hydro resources - modeling of storage, inlet and water flow
- Risk management – through scenario analysis comes the decision on optimal allocation of resources over a short or long period

5 TEST MODEL – POWER SYSTEM OF THE REPUBLIC OF CROATIA

Electricity needed to meet the consumption within the power system is produced in power plants, industrial power plants, and small-scale distributed sources or purchased from the energy market. Within the power system of the Republic of Croatia, the vast majority of electricity is produced in conventional power plants (thermos, hydro, including half production in the Krško nuclear power plant located in Slovenia). A significant part (sometimes more than 50%) of electricity needs are bought on energy markets and imported. Moreover, more than half of the total installed capacity within the Croatian power system consists of HPPs. Furthermore, some large industrial customers have their own energy sources (refinery in Rijeka etc.), and the share of small distributed sources such as small hydropower plants or photovoltaic cells is still not significant at this time. In recent years, installation of wind power plants has been intensified, and in August 2016 a total of 18 were connected to the transmission and distribution grid, with a total installed power of 420.95 MW.

All data used in modelling is used according to [9] and the low-carbon scenario of strong transition was taken into account. In (Table 1.) the production structure for the base year 2015 is presented as well as the planned installed power for 2030, 2040 and 2050. Figure 1 shows the geographic distribution of modeled existing thermal power plants and hydroelectric power plants. Moreover, an important part of the power system is a power grid that connects production capacities and consumers and provides safe, adequate and high quality electricity supply. The power grid is divided into two parts: transmission and distribution. The liberalization of the energy market brought the separation of transmission and distribution so know they belong to regulated market activities. The transmission network in the Republic of Croatia is owned by Croatian transmission system operator (cro. *HOPS*) while the distribution network is owned by Croatian operator of the distribution system (cro. *HEP ODS*). In this paper, a 400 kV transmission network with the largest nodes (Žerjavinec, Tumbri, Erenstinovo, Melina, Velebit and Konjsko) is modeled, and all the modelled production units are assigned to the particular node to the one they are geographically the closest. The predicted consumption is divided by nodes based on percentages of actual electricity consumption in those regions.

Based on the available hourly load profile from 2015, with a proportional annual increase in energy consumption, hourly electricity consumption was estimated and created up to 2050. Due to the electrification of transport and the anticipated higher consumption of electricity in industry and services, electricity consumption is estimated to have an average growth rate of 1.2% per annum from 2014 to 2030, and 1.7% growth from 2030 to 2050. In 2050 the consumption should be by 70.1% higher than consumption in 2014. The new production capacities of conventional power plants, with planned start-up dates, were determined based on data available from Croatian National Power Utility - HEP. New coal-fired power plants are not envisaged after decommissioning the existing power plants. In modelling the natural inflow for hydropower plants the average hydrology was taken into account. The installed capacity of the RES for 2020 is determined according to the quotas set in the Changes of the Tariff System for the Production of Electricity from the RES and Cogeneration (NN 100/15) by 2020. Also, the model does not envisage incentives for new wind and solar power plants (which enter after 2020), and it is assumed to continue stimulating the capacity for biomass and biogas, small hydropower plants and geothermal power plants. Regarding the emissions, the emission prices are set, as well as the annual limits for the production of CO_2 emissions. Modeled power plant candidates include all commercially available technologies. The CO_2 price rises to 90 €/ton, limits on CO_2 emissions of 1725 ktonnes since 2030 and 555 ktonnes from 2050. The electricity market is not modeled after the year 2030. The model does not allow unserved and dump energy, meaning that the demand must be met all the time and also no extra energy should be produced.

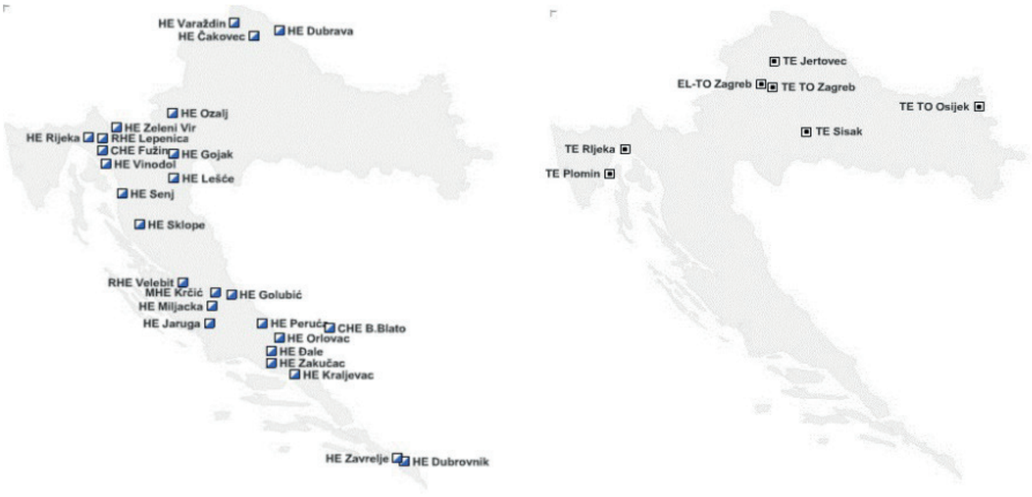

Figure 1. Geographical distribution of modelled existing hydroelectric power and thermal power plants

Table 1. Installed capacity

Installed power [MW]	**2015.**	**2030.**	**2040.**	**2050.**
TOTAL	4.786	8.434	10.718	12.643
Nuclear power plant	348	348	348	500
Gas-fired power plant	1.140	1.745	2.630	3.080
Coal-fired power plant	330	210	0	0
Gas-fired power plant with CCS	0	0	550	550
Heating oil-fired power plant	320	0	0	0
Hydroelectric power plants	2.095	2.567	3.107	3.107
Wind power plant	420	1.887	2.227	3.259
Solar power plant	48	1.300	1.400	1.667
Biomass power plant	28	94	140	150
Biogas power plant	21	100	128	136
Geothermal power plant	0	44	48	54
Small hydroelectric power plant	36	140	140	140

5.1 EV modeling

Battery electric vehicles (BEV) with vehicle-to-grid (V2G) technology were modeled. A total amount of EVs penetrating each year from 2020 to 2050 was divided into 20 EV objects that represent a set of EVs with corresponding annual capacity growth, according to the data available from [9]. The amount of EVs connected to the grid by 2030 is set to be 150,000, i.e. 4% of the total number of vehicles in 2030, and by 2050 a total of 1.5 million EVs or 75% of the total number of vehicles. Furthermore, it was necessary to set the maximum power that each vehicle has at a given time during the day (Figure 2. and Figure 3.). Hourly diagrams, made for working days and weekends or holidays, describe the movement of cars for each group of EVs object i.e. their consumption or production (Figure 4. and Figure 5.). Also, in order to successfully model the separation of EVs from the network, it was necessary to model the limitation related to their production. In other words, the production of each battery must be greater than or equal to the maximum power used by the EV at every hour of the day, so that there is a potential for EV to deliver power to the network and thus serve as an energy source. The anticipated consumption of EVs was added to the planned electricity consumption in Croatia by 2050. It should also be emphasized that, when modeling electric vehicles and their use in the system, investment costs for the construction of charging stations, as well as the supporting infrastructure and contents were not taken into account.

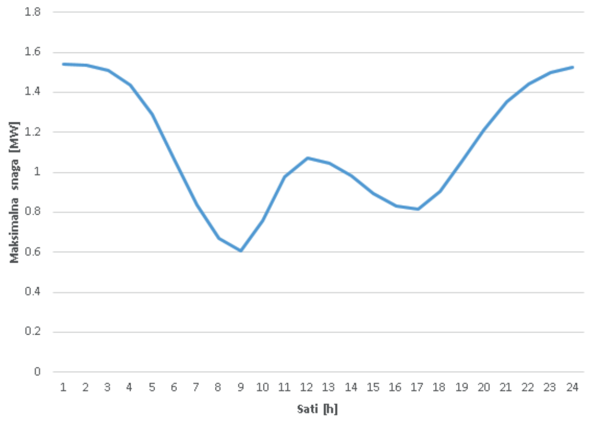

Figure 2. Hourly profile of maximum power of a group of EVs on working day

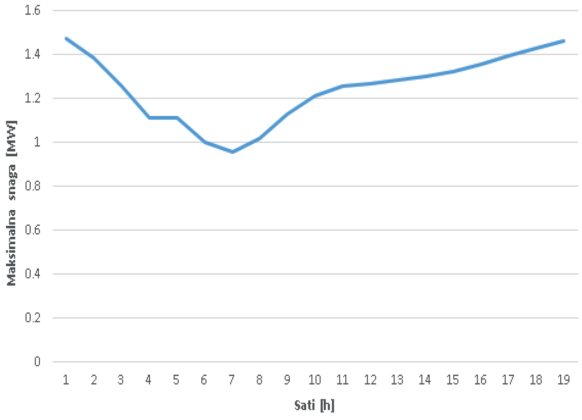

Figure 3. Hourly profile of maximum power of a group of EVs on weekends and holidays

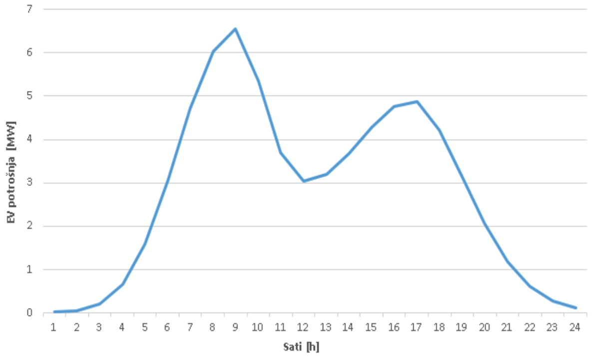

Figure 4. Hourly profile of energy consumption of a group of EVs on working day

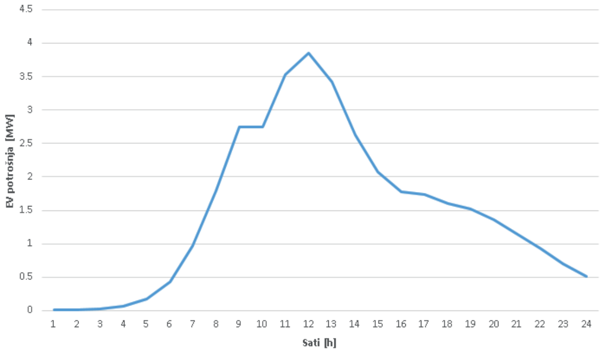

Figure 5. Hourly profile of energy consumption of a group of EVs on weekends and holidays

5.2 Wind power plants modeling

The existing installed capacity of the wind power plants as well as the anticipated entry of new production units into the grid in the period up to 2050 were modeled. Current and future production units are divided into nodes in the model by geographic position on the 'South Adriatic', 'Middle Adriatic' and 'North Adriatic'. For each area, based on the existing measurements and data from 2015 and forecasts, an hourly chart of wind farm production is defined by 2050. The generated hourly charts are associated with each existing and future production unit. An increase in installed wind power capacity for the analyzed years is shown in (Table 1.).

5.3 Solar power plants modeling

Existing solar power plants as well as anticipated production units are distributed into nodes in the model according to their geographical position to 'Inland', 'Primorje' and 'Dalmatia'. For each area, the hourly production diagram is defined by 2050, based on the measurements collected for the base year 2015 and the forecasts for the analyzed period. The increase of the installed capacity of solar power plants for the analyzed years is shown in (Table 1.).

6 RESULTS

According to the data described in Section 5, the test model of the Republic Croatia was created. The model consists of 12 nodes, of which 6 represent high voltage nodes, 3 high voltage nodes where the wind power plants are connected to the grid and 3 medium voltage nodes where the created solar power plants are connected. Furthermore, for the purposes of analysis, several scenarios have been created to help manipulate input data. The two main scenarios were observed and analyzed, scenario without EVs and pumped-storage HPPs and scenario with EVs and pumped-storage HPPs. Increase in the installed capacity of wind and solar power plants in the created model, for the observed years is shown in the following figure (Figure 6.).

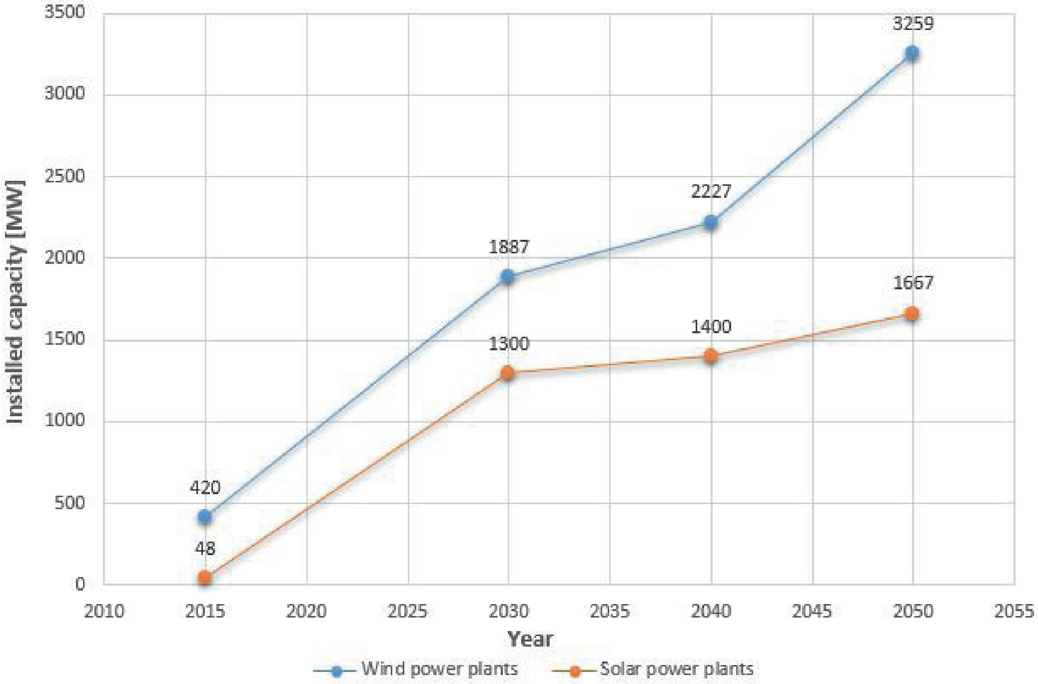

Figure 6. Increase in the installed capacity of wind and solar power plants for observed years

Impact on system flexibility can be observed by observing how much EVs and their quantity affect the production of certain power plants so that the lack or surplus production caused by intermittent production from RES is covered. Also, the production of RES themselves varies depending on whether there are or aren't EVs connected to the power system and whether the pumped-storage HPPs are constructed or not. When there are EVs and pumped-storage HPPs in the system, the total annual production from RES is higher (Figure 7. and Figure 8.).

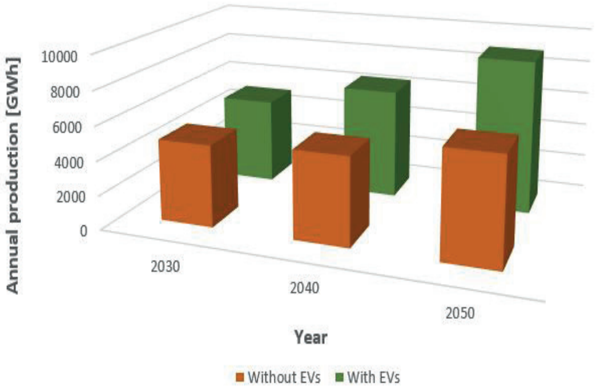

Figure 7. Annual production from wind power plants for both scenarios

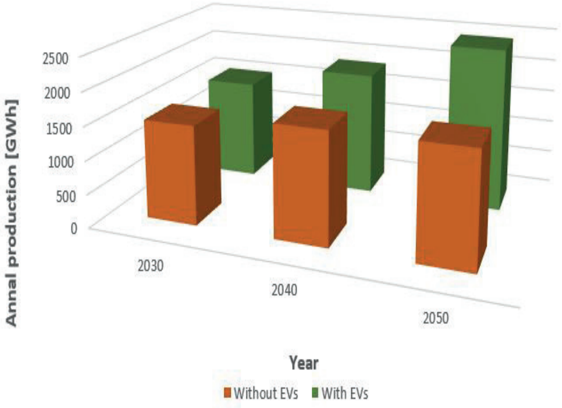

Figure 8. Annual production from solar power plants for both scenarios

An important influence on system flexibility is reflected in the production of fast ramping gas and slower coal thermal power plants, which in traditional systems without energy storage serve to cover the lack of electricity due to intermittent production from RES. In 2030 the increase of the EV capacity is relatively insignificant, therefore the increase of production from the wind and solar plants is only 270 GWh (Figure 9. and Figure 10.). However, it should be noted that the production from gas thermal plants is smaller in the EV scenario. Also, production from hydro plants is 2033 GWh smaller in the scenario without EVs. Results for 2040 are shown in (Figure 11. and Figure 12.). It is obvious that EVs cause a larger increase in total annual consumption than in 2030. For the scenario without EVs, the annual production from thermal plants is 33 GWh higher and the annual production from RES is 1441 GWh lower. Increased consumption caused by EVs is mostly covered by increased production from wind and solar plants, but also by an increase in production from hydro plants, which is 2907 GWh higher. In the case of 2050, the results are slightly different (Figure 13. and Figure 14.). Specifically, in the EV scenario, annual gas production is by 867 GWh higher than in the scenario without EVs. Obviously, the amount of 1.5 million EVs and modeled charging profiles cause a large increase in consumption in some periods (which coincides with the peak loads) that cannot be met by increased production from the installed RES and hydro plants, therefore the fast gas thermal plants increase their production.

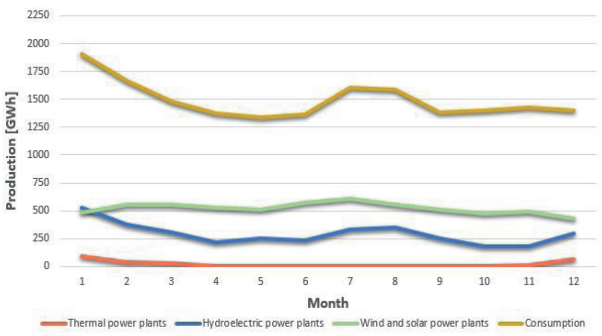

Figure 9. Production from wind and solar, gas thermal and hydro power plants for 2030 without EVs

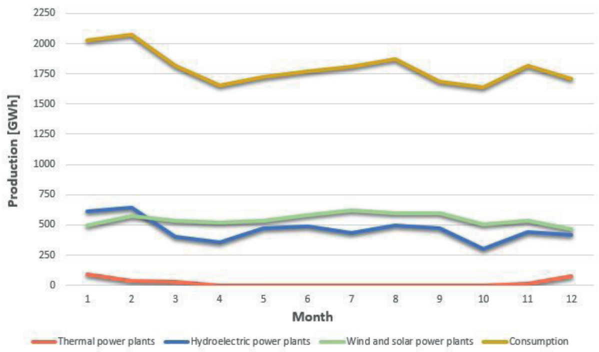

Figure 10. Production from wind and solar, gas thermal and hydro power plants for 2030 with EVs

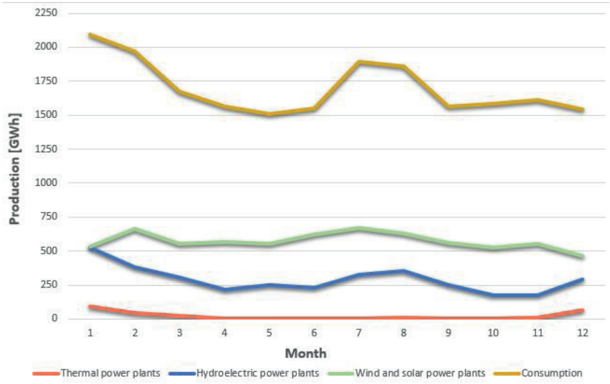

Figure 11. Production from wind and solar, gas thermal and hydro power plants for 2040 without EVs

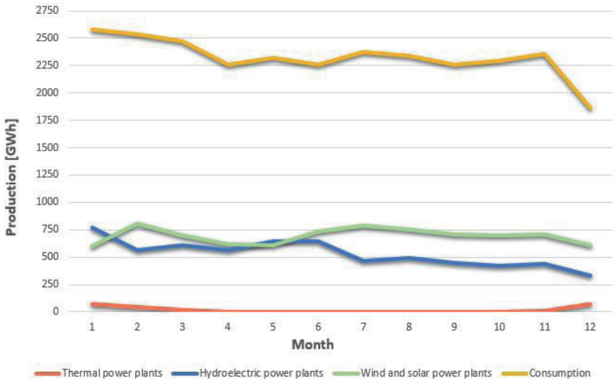

Figure 12. Production from wind and solar, gas thermal and hydro power plants for 2040 with EVs

Figure 13. Production from wind and solar, gas thermal and hydro power plants for 2050 without EVs

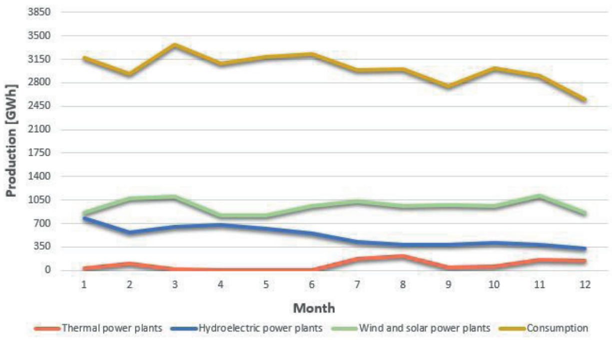

Figure 14. Production from wind and solar, gas thermal and hydro power plants for 2050 with EVs

In order to further examine the flexibility of the system, a new scenario has been made in which all thermal power plants, that can provide fast support for system balancing in the event of sudden changes in production from RES (primarily from wind power plants), have been excluded from the power system. After the simulation for the given scenario for three different observed years, the following data and conclusions are made and shown in (Table 2.).

Table 2. Flexibility of the power system for the new scenario

Year / Scenario	2030.	2040.	2050.
Without EVs and pumped-storage HPPs	It was not possible to satisfy all the simulation conditions	It was not possible to satisfy all the simulation conditions	It was not possible to satisfy all the simulation conditions
With EVs and pumped-storage HPPs	In the basic scenario, the number of EVs is insufficient to store enough energy	In the basic scenario, the number of cars is insufficient to store enough energy	The number of EVs in basic scenario (about 1.5 million EVs) allows the operation of the system without starting the thermal power plant

When there are no modelled EVs and pump-storage HPPs in the system, the simulator cannot find the optimal solution since the system does not allow unserved energy, i.e. the demand must be met at any period of time. In such a scenario, neither the newly installed capacity of renewable sources along with other conventional ones is sufficient or sufficient to keep the system in balance at all times.

For scenarios when there are electric vehicles and pump-accumulating hydroelectric power plants, the results differ depending on the number and capacity of the EV. Namely, from all scenarios and years only in the scenario with EVs and pumped-storage HPPs in 2050, it is possible to fulfil all the limitations of system and simulation settings.

For more detailed analysis one day was taken into observation. The selected day was July 15, 2050 since it is one of the months where production from wind and solar power plants is smaller, and hydroelectric power plants are also producing less because of a reduced natural water inflow. The year 2050 was chosen because the system has the largest available EV capacity in that observed period.

In (Figure 15.) it is clear that in the periods between 4 – 11 and 13 – 23 hours during the day the EVs provide the power into the power grid so that the lack of production from installed and operating power plants (conventional and RES) is satisfied. It is only around noon that the energy that the EVs are consuming from the grid is larger than the total energy that is delivered into the grid, so the net production is negative. The picture also shows the net production of pumped-storage

HPPs. It is obvious that in the moments when the EVs cannot deliver power into the grid, or at night when the batteries are being charged, pumped-storage HPPs produce electric power to meet consumption. The figure clearly show how modelled energy storage technologies complement each other.

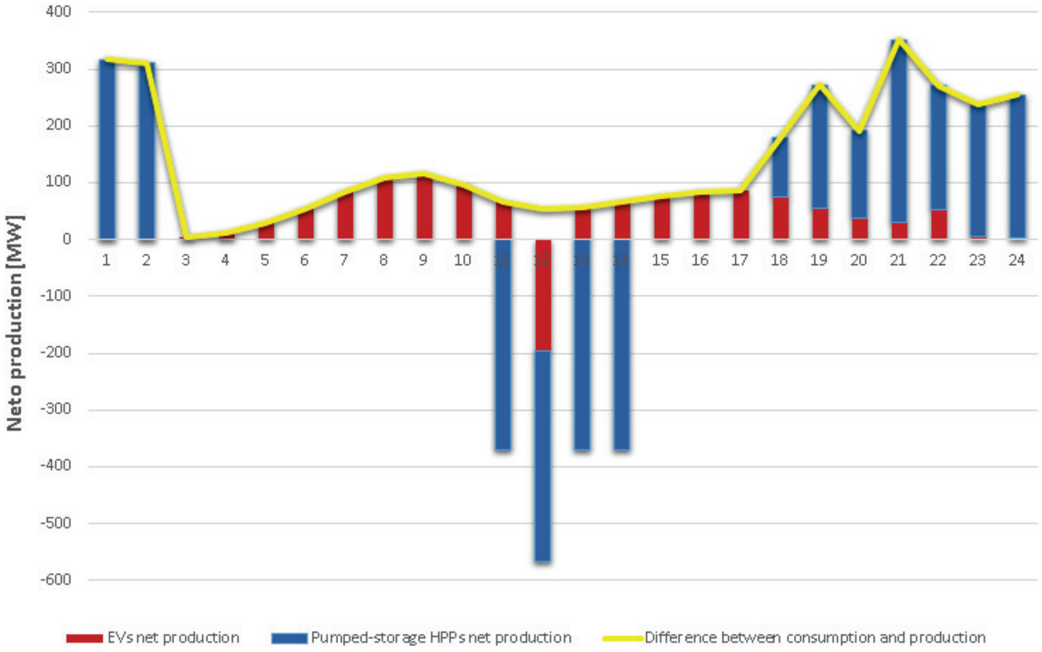

Figure 15. Net production of energy storage technologies in the system for 15.7.2050. for the scenario with EVs and pumped-storage HPPs

The impact of EVs on CO_2 emissions is one of the key parameters when analyzing the application of such energy storage technology. Namely, by increasing the share of EVs, emissions from the transport sector are shifted to the electricity production sector. Respectively, the emissions are shifted from non-ETS to ETS, which allows fulfillment of the targets set by the European Union for the observed period. The results suggest that in 2050 the additional load caused by EVs results in a small increase in CO_2 emissions since the EV charging was not modelled completely according to off-peak charging, therefore the EVs charging during peak load hours causes higher production from conventional fast power plants which contributes to CO_2 emission production. (Figure 16.) It can also be concluded that although RES capacity increases each year, the modelled growth around 2050 is not sufficient to cover the demand of the anticipated amount of EVs so the fast thermal power plants are started during some periods. Moreover, total production in both scenarios decreases over the years, which is expected as more and more RES enter the grid and conventional power plants are decomposed or they’re production is not needed.

Total production costs are calculated as the sum of all production costs, including fuel costs, variable operating and maintenance costs (VO&M), start-up cost, shutdown costs and emission costs. Comparing both scenarios it can be seen that in the case of the model with EVs the total production costs are lower during most of the analyzed period. Namely, as it was already mentioned, the production from RES in the scenario with EVs is higher and the costs of the production of such units are lower than conventional production units, hence the total production costs are somewhat smaller as shown in (Figure 17.). However, as in the case of CO_2 emissions, the higher production from thermal power plants in 2050, caused by the high number of EVs as much as the modelled charging profiles results in higher total generation cost.

Furthermore, the impact of modelled EVs and pumped-storage HPPs on total annual transmission losses is positive. Namely, due to the possibility of energy storage at locations closer to actual consumption, power flows are reduced and transmission losses in the power network are lower. (Figure 18.)

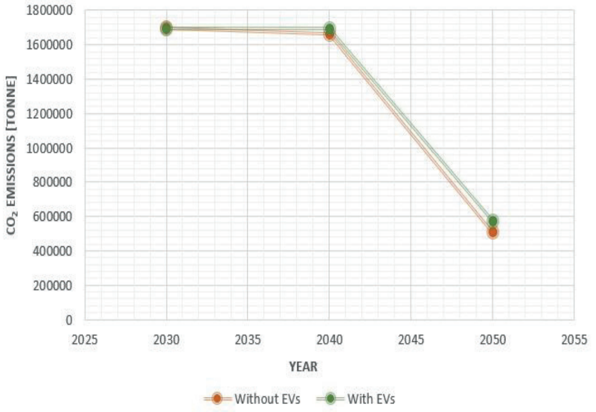

Figure 16. CO_2 Emissions for both scenarios

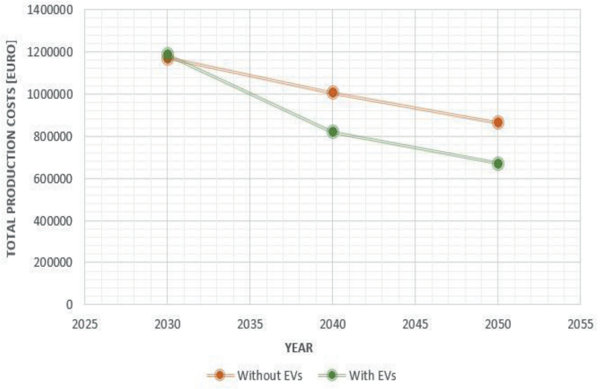

Figure 17. Total production costs for both scenarios

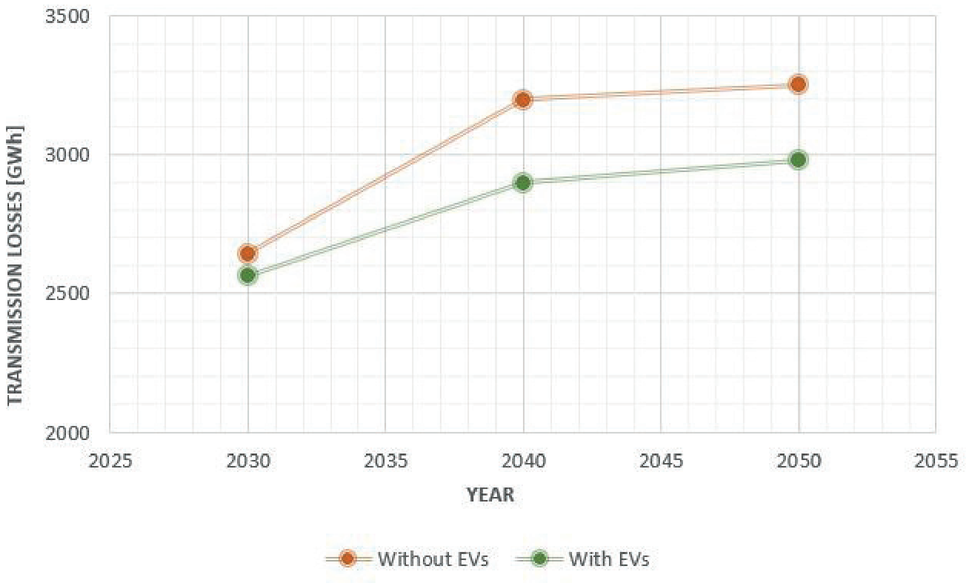

Figure 18. Transmission losses for both scenarios

6.1 Advantages and disadvantages of connecting EVs to power system

Based on the carried out analyses, and the results obtained in the previous chapter, the following advantages and disadvantages of electric vehicles can be concluded:

Advantages:

- Increase in production from variable RES – a higher increase in production from wind power plants.
- Reduced need for building additional conventional power plants to cover peak loads (with an increase in the number of EVs over the years the need for additional capacities of conventional power plants is decreasing).
- Decreased total production costs due to larger production from RES.
- Reduction of annual transmission losses.

Disadvantages:

- The need for a relatively large number of EVs to ensure sufficient capacity of energy storage.
- If the EVs are charging in periods of peak load, the conventional power plants with quick response must generate so that the additional load caused by high number of EVs is covered.
- Slight increase in CO_2 emissions compared to the scenario without EVs due to modelled charging profiles.

7 CONCLUSION

The European Union is the leader in the integration of renewable energy sources in the world. The latest directives intensify the construction of power plants using renewable sources. With the increase in production from renewable energy sources, or by increasing share of renewable energy sources in total consumption, it is being endeavored to reduce the dependence on energy imports as well as to contribute to the reduction of GHG emissions. The largest share in newly-installed capacities around the world is occupied by wind power plants. Wind power plants cause instability of the power system because of the volatility and unpredictability of the wind (especially on the long term basis) as a source of the energy. This raises the costs of maintaining the system in balance and in certain situations can lead to instability and even system breakdown. There are being options discussed, and as one of the most possible and prominent option are integration of EVs into the grid. The role of pumped-storage HPPs has already been recognized and there is a total installed capacity of 168 GW in the world. Pumped-storage HPPS are most often used in terms of energy arbitrages, i.e. during the off-peak periods, when the electricity price is lower, electricity from the grid is used for the pumping of water from the lower to the higher water tank, and in the periods of higher demand, when the electricity price is higher, water flows through the turbine, which drives the generator, into the lower water tank, and produces electricity. One of the main advantages of pumped-storage HPPs is their synergy with variable energy sources, such as wind and solar power plants. This is due to the fact that pumped-storage HPPs can provide an instant reserve that can be utilized for a period of several seconds to several minutes when other variable RES are unavailable or their production is sudden abrupt.

The results based on the analysis made for both scenarios without and with EVs in the power system show that additional storage in a form of EVs allows increased production from RES, decreased need for building additional conventional fossil fueled thermal power plants to cover peak loads. Thus the total generation costs are lower and also the transmission losses are decreased. The observed deficiencies in this model are that a relatively large number of EVs is needed to ensure sufficient energy storage and if the EVs are charging in periods of peak load, the conventional power plants with quick response must generate so that the additional load caused by high number of EVs is covered. This as well causes a slight increase in CO_2 emissions compared to the scenario without EVs.

Further development of the model would include more detailed data on production units as well as expansion of the model of the whole region by creating production and consumption of neighboring countries, thus giving a better picture of cross-border transmissions, which would ultimately result in a more accurate picture of the Croatian power system. It would certainly be desirable to analyze scenarios with and without electric vehicles, but including the costs of the building of the charging stations. Also, further upgrading would be a detailed analysis (say, on a monthly basis) on how much wind and solar power plants are producing depending to their maximum capacity factor when there are no EVs in the system and when they are included in the model.

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