Long-term Energy Planning of Croatian Power System using Multi-objective Optimization with Focus on Renewable Energy and Integration of Electric Vehicles

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ABSTRACT

Due to the stochastic nature and variability of renewable energy sources (RES), it is necessary to integrate still expensive storage capacities into an energy system with a high share of RES and to model appropriate energy market. The study presented here considers all energy carriers, however, only the electricity carrier is modelled in detail, with notion taken for the heating demand that is covered but without proper modelling of storage.

A two-level approach in which multi-objective optimization was used on the global level to design a complex Croatian Energy System (CES), where electric vehicles (EVs) that are integrated to serve as battery storage in Vehicle-to-Grid (V2G) mode for a scenario between 2015 and 2050. In addition, case study includes nine aggregated hydro power plants, one for each river basin in Croatia. Also, case study includes solar and wind power plants modelled for six locations in Croatia: Osijek, Zagreb, Rijeka, Sibenik, Split and Dubrovnik. The resulting Pareto front suggests that with assumed future costs of fuels and technology certain level of conventional energy sources will have to remain in the energy system to take into the account unfavourable weather conditions and to cover heating demand, which also results in significantly lower load factors for those power plants. Also, variants with more RES share have lower total energy system load factor and significantly higher installed capacity.

KEYWORDS

renewable energy sources, electric vehicles, vehicle to grid, long-term design of energy system, multi-objective optimization

1 INTRODUCTION

Today it is important more than ever to take sustainable path in designing future energy systems. In December 2015 at the 21st UN Conference of the Parties (COP21) global agreement to keep the rise in global mean temperature below 2°C was achieved. It is clear that energy sector will play critical role in reduction of greenhouse gas (GHG) emissions as a main contributor with almost two-thirds of all anthropogenic GHG emissions [1].

Declared as a strategic goal, for energy production from RES certain assumptions are taken regarding the layout of future energy systems. Higher emphasis is placed on improved possibilities of transmission, transport and storage of energy in the energy system and matching of demand and production in two dimensions. First dimension is the time component, where a surplus of production in night-time or a shortage in day-time occurs. Similar effects are visible on longer time scale in seasonal and annual differences, such as hydrological differences. The changes require use of energy storage, such as hydro accumulation, various types of chemical batteries, ultra-capacitors, flywheels, compressed air storages, heat or cold storage and conversion to synthetic fuels. Second dimension is the geographical one, in which the location of production does not overlap with the location of demand. Electrical system solution requires the development of a robust transmission network, capable of handling the transfer of more units of energy in time than ever before. An ever increasing number of long-distance power lines are proposed, with nominal voltage above the standard 400 kV, as well as a switch from AC transmission to DC, with voltages of 400 kV up to 1000 kV.

Aside from these dimensions, a question of choice of an energy vector, or energy carrier is asked, which implies transformation of energy between energy vectors with optimal performance. Stated problems require a unified approach to optimization and regulation of a system, and it is assumed that by better defining individual parameters significant savings could be achieved in the process. Integration of RES and the electrification of the transport sector pose further requirements on the system flexibility. In 2012 The transport sector had a 20% share of global energy- and process-related CO_2 emissions and accounted for 27% of total global final energy consumption soit is the sector with high possibilities for energy rationalization [2].

Similar demands exist in the building industry, where electrification could be achieved by converting electrical energy into heat energy via heat pumps or electro resistive heaters, in individual or centralised systems. Synthetic fuels are one of the solutions for long-range transport needs in shipping and airline industries.

1.1 State of the art

Previous research in this area was oriented towards development of software models to predict demand, production management and decision support systems. A set of over 40 models was analysed by Connolly [3]. EnergyPLAN model was applied to 15 studies for calculation of

High-RES scenarios and more than 30 studies for showing capabilities of integration of RES into the energy system [4].
The H2RES model works on similar principles and it became one of the models to enable precise modelling of energy systems by means of modelling individual components of the energy system [8]. The work consisted of modelling of primarily isolated and island systems [9]–[12]. Basic difference of H2RES and other related models is in the ability to model individual power plants with the hourly time step resolution.
eMix model recently described in [13] provides the bottom-up optimization of long-term generation expansion planning. This tool uses annual time step for calculations while short-term requirements of the power system in terms of balancing and reserves it solves for the worst case in one day or selection of more problematic days. The eMix author's avoided to make hourly balancing through each hour in year to save computing resources.
Accordingly, H2RES which calculates energy balance for 8760 hours in each year in selected time horizon demands more computer resources. For those reasons the research continued towards the optimization of the super-structure, firstly by applying domain knowledge through RenewIslands methodology [14]–[16] in combination with the optimization software TOP Energy [17]. A general overview of existing methodologies was described by Manfren [18]. In [13] authors are also comparing several energy planning models by their technical characteristics with particular remarks on optimization and MILP programing. Another issue addressed through H2RES is the ability to model differently each year of the scenario. These aspects depend on the fact that the optimization determines what resources to install and when. Specific goals can be set to enable entry into service or decommissioning of components in a given year, and demand is automatically changed for each year regarding user inputs. Most advanced model of that kind was developed and tested by Zhang [19]. The aim of H2RES model is to integrate multi-year calculation with advanced optimization methods to produce model for long-term energy planning of energy systems of all sizes.

Other research showed it was possible to scale the dimensions of the system for even larger systems, such as national energy systems, with a higher number of power plants and optimize them in terms of installed capacity and management. Results by Bussar [21] assumes an installation size for a 100% sustainable European energy system of 2500 GW of RES, and an energy storage capacity of 240 TWh. Current capacities are nowhere near the scale mentioned in the work, and further analysis is required. Flores et al. [20] optimized investments in large scale energy system and proposed a multipored disjunctive optimization model to maximize the Net Present Value (NPV) of the energy sources. They made important conclusion that results of optimization highly depends on adopted parameters e.g. on fuel prices, or costs that are influenced by external factors such as political or environmental constraints. As models can quickly calculate different scenarios it can be used to help decision and policy makers in setting up framework for development of energy systems.

Of particular interest is the energy storage component of the energy system. As an arbitrage mechanism, the optimization focuses on the higher levels of RES integration to supplement the work of storages. Critical aspect of this component is determining the appropriate costs, expressed in terms of Levelised Cost of Energy (LCoE), as described by Pawel [22]. To accurate calculate LCoE on the long term in large scale energy system it is necessary to incorporate unit commitment costs and constraints as proposed by [13] or [24]

For electrical grids with low capacities of transmission, it is beneficial to complement it with a storage technology to mitigate variations in the load and production, specifically in high-RES and microgrid levels, stated in the work of Etxeberria [23]. A growing market for energy storage is in the area of EVs, with their benefits in smart grid environment determined by Stadler [25], and shortfalls when coordinated charging and discharging for Vehicle-to-Grid (V2G) operation is not properly implemented [26]. Comparison of two national energy systems with significant classical storage technologies and scenarios with and without EVs V2G implemented were conducted by Kempton [27]. The main issue of this approach lies in the aggregated battery model which does not take into account the variability of storage capacity created by non-stationary battery application. Secondary problem is that of EV driving cycles, for which there is still no good substitute apart from poll-based modelling and traffic flow estimates. These can be mitigated by properly applying long-term forecasting of demand in the transport sector [28], as modelled by Puksec. The paper was used as a basis for input data into H2RES for the national case study. Latest research from Connolly [29] shows the techno-economical analysis of converting Ireland to 100% RES in the near future. While there are some similarities, Croatia's system is less in need of an overall heating sector overhaul due to climate conditions, however it is comparable in the areas of grid regulation. A more correct comparison to the view taken by the authors is in the work Mathiesen [30], especially with the proposal on smart energy systems in the electricity sector and management of energy storages.

The optimization part of the model was based on the classification of optimization problems and preffered solutions in the work of Biegler [31] and problems in the global optimization and mixed-integer calculation for large-scale optimization [32], [13], [24] . The presented case was initially oriented towards microgrid optimization [33], due to system complexity, with references to work of Obara and Ippolito [34], [35]. Sinha provided a general overview of hybrid energy systems [36]. The work of Perera [37] describes multi-objective and multi-criterial aspects of hybrid system optimization. Initial methodology of the optimization was given in the work of Prebeg [38], [39], while the optimisation criteria were given by Østergaard [40]. H2RES model is in that aspect more similar to the Energy Hub approach of Schulze [41], relying on mathematical modelling and setting aside implementation of evolutionary algorithms used in the previously mentioned super-structure model, as implemented by Voll [42]. Super-structure still has the advantage of being automated in terms of topography [43], where H2RES requires more detailed inputs. On the other hand, the model is not constrained by practical aspects of the need to be converted into a GAMS model, and all solvers are kept within the framework of H2RES.

2 LONG-TERM ENERGY SYSTEM DESIGN METHODOLOGY

The methodology presented below is intended to provide a solution for a long-term, national level, energy system design problem. In a further text, it is applied to a CES design for the period from 2015 to 2050, however it can be applied a long-term design of other large energy systems. Formulation of the total optimization problem for a long-term ES design is similar as in Dubrovnik regional study [33]:

$$\begin{gathered} \min NPV \\ \min \overline{NPV} \quad \left(P_{N0i}, \Delta P_i, r_{i,t}\right) \\ \max RESSh \\ s.t. \\ \sum_{i=1}^{N_p} e_{i,t}\left(P_{N0i}, \Delta P_i, r_{i,t}\right) \geq D_t \\ RwHESsh_{2020} \geq 39\% \\ t = 1,2,..24 \cdot 365 \cdot 36 \\ i = 1,2..N_p \end{gathered} \tag{1}$$

where:

P_{N0i} Nominal power of power plant i (in starting year y_{0i}) (in MW)

ΔP_i Yearly increase of nominal power of power plant i (in MW)

$r_{i,t}$ Regulation of power plant i in a hour t

NPV Net present value of designed energy system (in EUR)

$\overline{NPV}$ Net present value normalized by the total energy produced to cover demand (in EUR/MWh)

RESSh Ratio of energy produced by the RES in designed energy system (in %)

$RwHESSh_{2020}$ Ratio of energy produced by the RES (with included hydro) in year 2020

$e_{i,t}$ energy produced by power plant i in a hour t,(MWh)

D_t electric energy demand (consumption) in a hour t, (MWh)

N_p- Number of power plants

As can be seen in (1), the design process is guided with financial based objectives, minimization of NPV and minimization of $\overline{NPV}$, which are usually the most relevant criterion for decision makers. The maximization of RES capacities reflects the tendency of policy makers in Croatia to increase the RES share beyond the EU goals. The main constraint is the satisfaction of the hour based energy consumption.

The RES share with and without hydro energy is calculated separately in order to clearly see contribution of different sources in achieving energy policy goals for production of electricity from renewable energy sources. As large hydro power plants represent sources with largest variability on the yearly time scale with significant impact to the environment in construction phase they should be modeled separately.

The nominal power of power plant i in year y ($P_{Ni,y}$) is determined by the simple model:

$$P_{Ni,y} = \begin{cases} P_{N0i} & |y = y_{0i} \\ P_{Ni,y-1}, & |y\%u_i \neq 0 \\ P_{Ni,y-1} + u_i \Delta P_i, & |y\%u_i = 0 \\ 0 & |y \geq y_{Di} \end{cases} \quad (2)$$

where:

$P_{Ni,y}$	Nominal power of power plant *i* in year *y* (MW)
P_{N0i}	Nominal power of power plant *i* in starting year (in MW)
y_{0i}	Starting year in which power plant start energy production
y_{Di}	Power plant *i* decommission year
ΔP_i	Yearly increase of nominal power of power plant *i* (MW)
u_i	Update interval of power plant *i* (years)
%	Modulus operator

This model enables start-up and decommission of power plant inside of the energy system design period. All parameters of this model could be treated as variable, however in the case study presented later, only P_{N0i} and ΔP_i are used as design variables. Regulation of power plant *i* in a hour *t* is handled by the variable $r_{i,t}$ that can have value between 0 and 1 for the powerplants, while the storages can have value between -1 and 1. Negative values implies that storage powerplant, is working in storage mode, while the positive values implies discharging or the powerplant mode. EVs that can work in V2G mode can also be added to the problem as a specific type of the storage. EVs modelling used in the conducted CES study is explained in 3.7.

As can be seen solving of total optimization problem would include huge number of regulation variables (7300 for each power plant/storage) which prevents the practical solving in that form. As described in [33], for a real world application, total problem described above can be solved by decomposing the total problem on the Global and Local problems as described in [33]. It is interesting to mention that the global optimization problem still remains controlled by the financial and policy related objectives, while the local optimization problem is oriented to the minimization of produced energy in some interval (one hour or 24 hours) which is important from the operational perspective. A practical solution for an energy system design is usually obtained using the hour-based merit-order approach (designated as Problem solution 1 in [33]), however, the other presented approach, (designated as Problem solution 2 in [33]), clearly outperforms the first approach for energy systems with high RES share and available storage capacity from EV. The global problem of the Problem solution 2 is the same as in Problem solution 1. On the local level, the problems are divided in 24-hour local single-objective (minimization of operating costs) optimization problems in which regulation variables of non-RES power plants and EV storage secures availability of electricity to satisfy the demand side of the energy system. Choice of a 24-hour period for the extent of each of optimization problems is governed by the behaviour of the EV drivers, and is mostly determined by their day-based obligations. Electrical energy demand forecast and meteorological forecast are very accurate with today's approximation/prediction models.

The disadvantage of the Problem solution 2 is the computational complexity, which have been reduced by the practically applicable sequence in the regional case study (see Figure 6 in [33]). However, even that procedure was too time-consuming for application in the national case study.

The approach proposed here introduces an additional modification, given as Problem solution 3 in (3) and (4) that reduces number of local optimizations that handles storages. Instead of finding regulation variables that handles storage charging for each day, $s_{lc,j}$ variables at global level determines days with level of load for which storage needs to be fully charged for the full discharge during the days' peak-load. In that way the complex optimization problem with storage charging has been eliminated from ~ 70-90 % level 2 problems.

Problem solution 3

Level 0 (Global problem)

$$\begin{gathered} \begin{matrix} min\ NPV \\ min\ \overline{NPV} \\ max\ RESH \end{matrix} \quad \left(P_{N0i}, \Delta P_i, s_{lc,j},\ {}^{1}e_{i,t},\ {}^{1}Mc_t\ \right) \\ E_{im,y} = \frac{\sum_{t=1}^{1,2,..24\cdot 365}\left(D_t - \sum_i^{N_P}\ {}^{1}e_{i,t}\right)}{\sum_{t=1}^{1,2,..24\cdot 365}\left(\sum_i^{N_P}\ {}^{1}e_{i,t}\right)} \leq 4\% \\ RwHESsh_{2020} \geq 39\% \\ t = 1,2,..24\cdot 365; \\ i = 1,2..N_p \\ j = 1,2..N_s \\ y = 1,2..36 \end{gathered} \tag{3}$$

Level 1 (Local problems, T=24h)

$$\begin{gathered} min\ \sum_{i,t}^{N_P,24}\left[f_{i,t}\left(\ {}^{0}P_{N0i},\ {}^{0}\Delta P_i,\ {}^{0}s_{lc,j}, r_{i,t}\right) + Mc_t\right] \\ s.t. \\ Mc_t = \left[D_t - \sum_i^{N_P} e_{i,t}\left(\ {}^{0}P_{N0i},\ {}^{0}\Delta P_i,\ {}^{0}s_{lc,j}, r_{i,t}\right)\right] mc_t \\ t = 1,2,..24;\ i = 1,2..N_p \end{gathered} \tag{4}$$

where:

$s_{lc,j}$	Storage load centile (1-100) identifies days in which storage *j* will be forced to charge in order to enable maximum daily discharge
mc_t	unit electricity price on electric energy market at hour *t*
Mc_t	Price of the energy bought on the market to cover insufficient energy production in hour *t*
$f_{i,t}$	Total variable expenses (operating maintenance and fuel) of energy production for power plant *i* in a hour *t*
$r_{i,t}$	regulation of power plant *i* in a hour *t*

Note: left superscript denotes parameters determined at another problem level, e.g. ${}^{0}P_{Ni}$ in (4) means that P_{Ni} is determined at level 0 (global level). That means that regulation variables $r_{i,t}$ are the only design variables present on local level optimization problems.

For the realistic long-term, national level, energy system design it is necessary to include the optimization problem formulation that includes the electrical energy market. Problem solution 3 given in (3) and (4), replaces constraints that have secure that total produced electric energy satisfies total energy consumption in each hour by the penalization of energy insufficiency. The penalization is added to Level 1 objective function in a way that energy insufficiency in hour *t* is multiplied by the price of electricity available at market at the same hour.

At global level, calculation of NPV now includes cost of the purchased energy while dependence on the electricity from market is regulated by the constraints which specify that imported energy in each year of scenario has to be less than 4% of produced electrical energy.

3 LONG-TERM DESIGN OF CES

3.1 Overview of current state of CES

As assumed for year 2015 the CES's installed capacity consists of primarily large hydro power plants (HPP – 48.29% capacity, size over 1 MW) and thermal power plants (TPP – 37.70%). The rest of the balance is covered by 50% co-shared nuclear power plant (NPP – 7.84%) Krsko, situated in Slovenia, and renewable energy systems (RES – 6.17%). Under RES, small hydro power (sHPP) (under EU regulation <10 MW, for the case and national legislature <1 MW), wind power plants (WPP), solar power plants (SPP), geothermal power plants and biomass power plants are included. All data in this chapter is acquired from the 2013 yearbook of Croatian utility provider HEP [44], and the website of HEP [45], unless otherwise noted.
In terms of capacity, HPP had 2143 MW of installed power, TPP 1673 MW, with additional 1428 MWt for district heating, hot water and industrial purposes on three locations in the country. Sole NPP, Krsko has a full capacity of 696 MW, with 348 MW available to Croatia, while RES installations were at 274 MW, as presented in Figure 1.

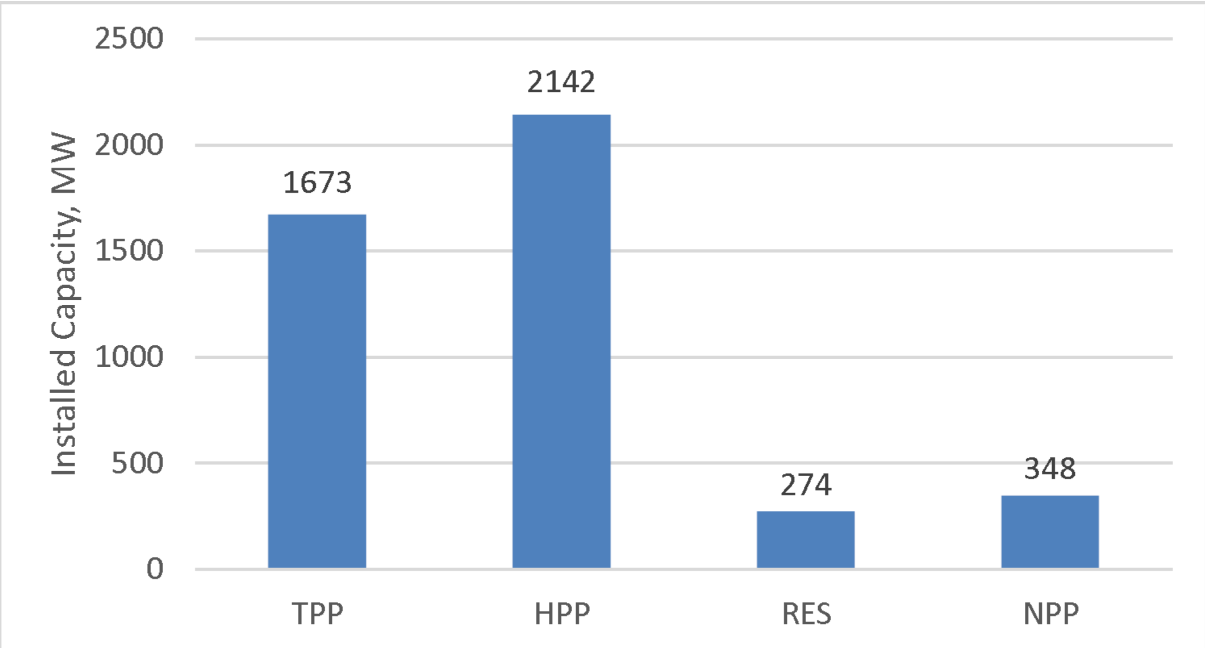

Figure 1. Installed capacity of power generators in CES in 2013

In terms of numbers of installations, HPP is represented by several major Croatian rivers (Drava, Krka, Cetina, and interconnected rivers of Dobra/Mreznica/Kupa, Lokvarka/Licanka, Lika/Gacka) with several minor rivers (Rjecina, Zrmanja) and one river in the neighbouring Bosnia and Hercegovina (Trebisnjica). Several other rivers, such as Sava, offer potential for further development of around 150 MW installed capacity. Current installed capacity per river basin is shown in Figure 2.

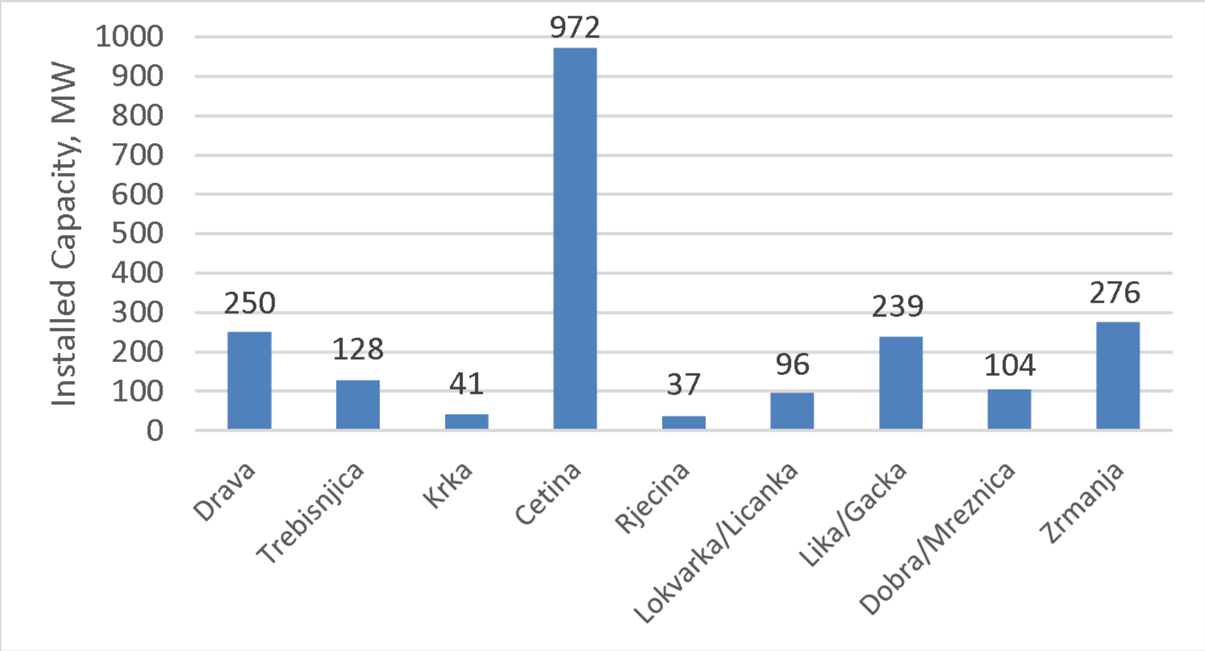

Figure 2. Installed capacity per river basin in 2013

Regarding TPP, these can generally be divided into three categories. Classic coal-fired TPP for base-load power, classic open-cycle gas cycle TPP which are used as peak-load plants, and combined-cycle gas TPP which are used for supplying district heating, hot water and industrial use of steam or hot water. Combined-cycle TPPs are located close to the major areas of urbanisation in the continental part of Croatia. Most of the boilers are fitted to use either natural gas or light fuel oil, although fuel oil is only used in extreme conditions. The cities with district heating grid connected to large TPP are Zagreb, Osijek and Sisak. Other smaller cities use district heating on a local-level, such as Velika Gorica, Zapresic, Slavonski Brod and Karlovac. The TPP capacities are displayed in Figure 3.

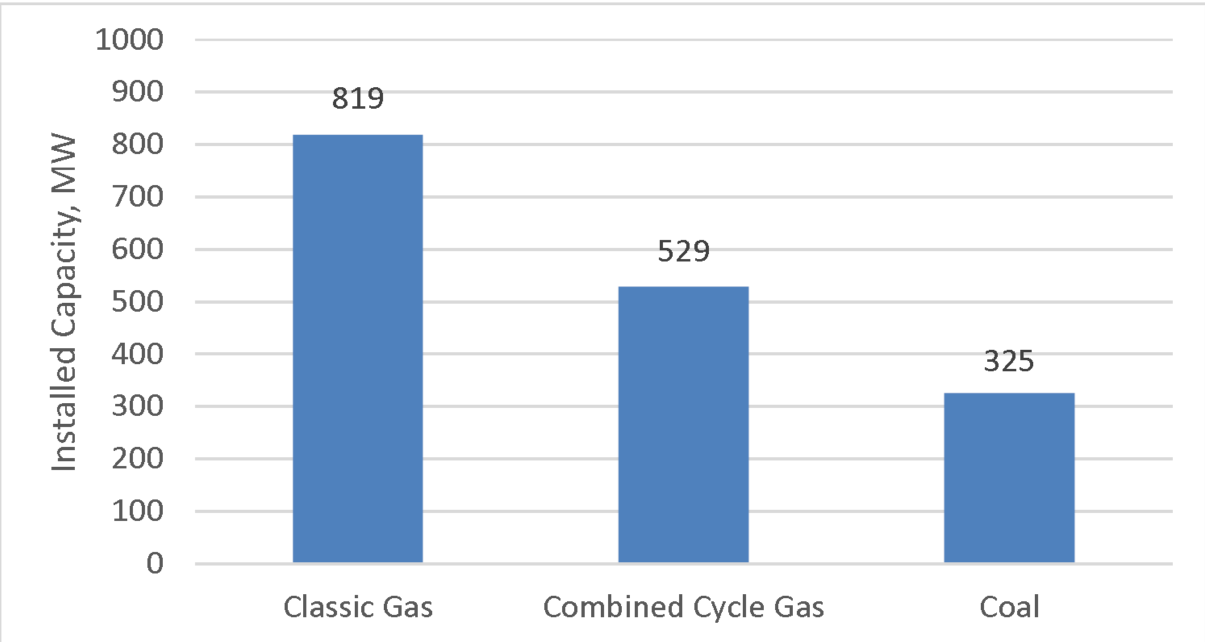

Figure 3. Installed capacity of TPP generators in 2013

RES in CES is heavily oriented towards wind power, with the Feed-in-Tariffs (FiT) for wind solar, biomass and geothermal installations, and the current quota of 400 MW of installations for wind has been allocated. In second place solar PV power is represented with 12.66 MW. The major obstacle in the previous years was very limited FiT for solar of only 1 to 2 MW annually. The quota has been raised to a total of 54 MW until 2020. Other RES contributors are biomass and biogas plants and small HPP. The overview of current and planned installations [46] is given in Figure 4.

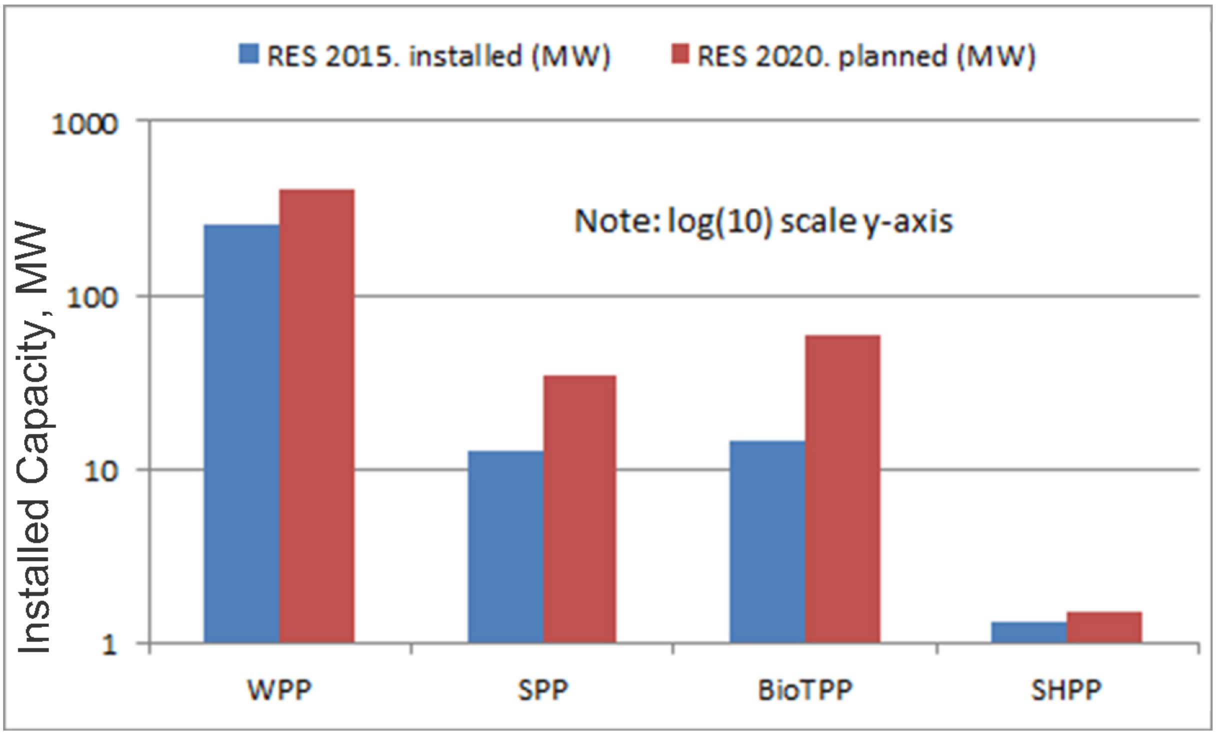

Figure 4. Planned RES capacity in 2015 and 2020

3.2 Demand of CES in the referent year and future projections of demand

Two types of energy consumption demands are investigated for CES. Primary concern is given to the gross final electricity consumption, which was on the order of 17.59 TWh in 2011 [47]. As a referent, year 2011 was taken into account. The average yearly increase was taken from NeD model and established at 0.05%, with an overall increase of 19.68% in 2050 in regards to demand from 2011, or 17.68% with the estimated demand of 17.89 TWh in starting year 2015. Yearly average increase ranges from 0.0048% to 0.081%. The load curve is presented in Figure 5, while the basic statistics for the data from figure are listed in Table 1

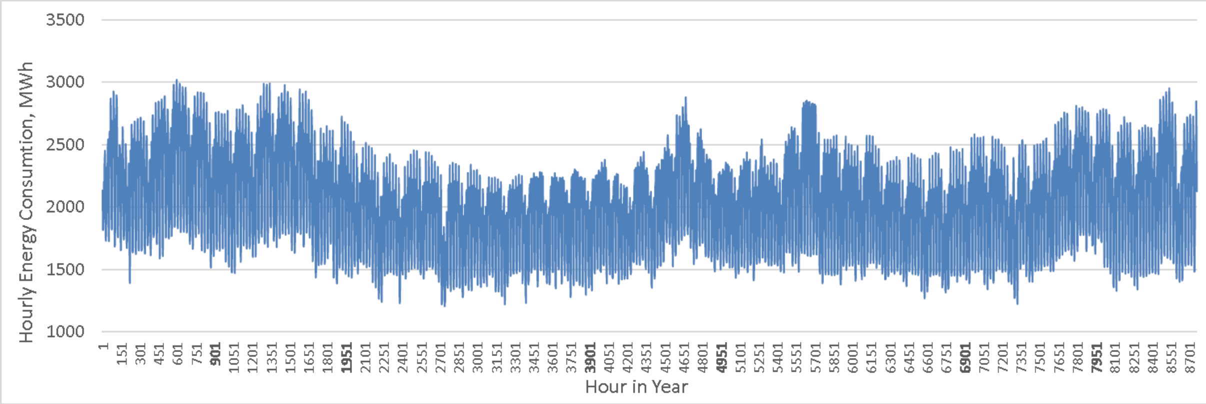

Figure 5. Anticipated electrical energy consumption for CES in 2015 (scenario starting year)

Table 1. Demand statistics for referent year 2011 and scenario starting year 2015

	2011	***2015***
Maximum (MWh)	2970	3021
Minimum (MWh)	1185	1205
Average (MWh)	2008	2042
Sum (TWh)	17.59	17.89

Secondary demand is the heating demand. This demand consists mainly for supplying the heating needs of urban centres with combined-cycle TPP (Zagreb, Osijek, and Sisak). The Heating Degree Days (HDD) curve was used to calculate hourly distribution curve of heating demand with the yearly increase of 2%.

As the national case study incorporates a time horizon until 2050, a degree of dynamics must be included to account for change in population, increased demand, and variance in the inflation. The long-term predictions are based on the study given in [28] and [48]. The estimated consumptions for the period 2015-2050 are given in Figure 6 for electricity demand. It is important to mention that given electricity consumption is without electricity consumption of EV. Charging and discharging of EVs is defined in EV model below.

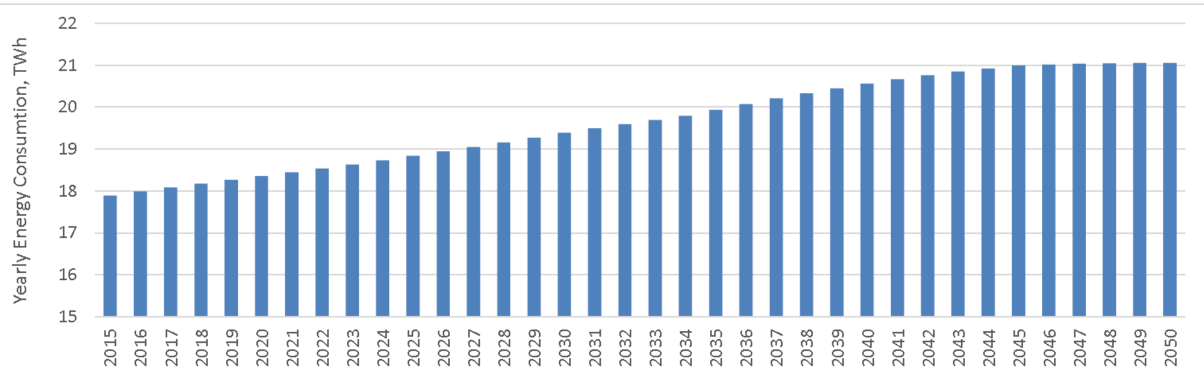

Figure 6. Estimated electrical energy consumption in TWh up to 2050

3.3 Hydropower modelling in H2RES

The description of the used power plant models in H2RES are given in references [8], [10], [11] and [33]. As a part of research presented in this paper, hydro power plant model has been developed since HPP produces dominant part of CES electrical energy.

Typical HPP types are run-of-river, accumulation and reversible (pumped hydro) HPP. Each is represented in CES, with the following setup in Table 2. The representation of type refers to P – run-of-river, A – accumulation, R – reversible or pumped hydro type installation.

As it is noticeable, the largest portion of HPP fleet is of the accumulation type, and requires good understanding of HPP abilities to compensate for the daily demand diagram with the accumulation that is available to each HPP. As most of the HPP are situated on the same river or river basin, these operations are interconnected. The list of accumulation bodies of water along with their groupings according to the river basins is given in Table 3.

For Lake Bileca on Trebisnjica River, the actual useful accumulation capacity is 1082 million m^3, however, the hydrology data was not available, and it was modelled only with the compensation basin at disposal.

Generally, accumulations and their adjoining HPP can be divided into daily, weekly, monthly and seasonal accumulations. The type is determined by the amount of time it is possible to operate an HPP in nominal power. This factor is constrained by the capacity of the lake behind the HPP, and the amount of flow in the river, determined by the hydrology of the system in question.

Reversible or pumped HPP installations in CES are limited to one large installation (RHE Velebit) that was planned as a part of the nuclear power plant installation which was never realised. Other installations are smaller units in the order of <10 MW serving various river basins and artificial lakes in order to balance the inflow and outflow of the temporary accumulation. One major pumped HPP installation is RHE Velebit, situated close to Zadar; with 276/240 MW installed turbine/pump power. The round-trip efficiency of that installation is on average 76.6%, with the down flow in turbine mode of 60 m^3/s, while the pump mode up flow of up to 40 m^3/s.

Run-of-river HPP in CES are typical installations using the available flow of the river and in some cases utilise a small basin to divert the water needed for operation.

Small HPP are a subject of constant investigation in CES. There is limited investment with only 2.47 MW of installed capacity, some more than 100 years old. The main obstacle remains in the area of legislature, where it is very difficult to obtain a building permit. Most investments at this moment are being developed on existing dams using biological minimum water flow to add further generator sets with small installed power (typically <2 MW). For the purposes of the national case, all sHPP are regarded as run-of-river installations, associated with the basin they are installed at.

Table 2. Existing HPP production historical data and load factors

Type	*Name*	*Nominal Power (MW)*	*Average production 2009-2013 (GWh)*	*Average 5-year Load Factor*
P	HE Varazdin	94.58	486.66	58.74
P	HE Cakovec	77.44	391.20	57.67
P	HE Dubrava	77.78	388.32	56.99
P	HE Rijeka	36.8	93.48	29.00
A	HE Vinodol	90	145.82	18.50
R	CHE Fuzine	4.6	3.82	9.48
R	RHE Lepenica	0.8	0.40	5.72
A	HE Zeleni Vir	1.7	6.91	46.37
A	HE Senj	216	904.68	47.81
A	HE Sklope	22.5	76.16	38.64
P	HE Gojak	55.5	198.18	40.76
P	HE Ozalj	5.5	21.72	45.08
A	HE Lesce	42.3	55.62	15.01
R	RHE Velebit	276	488.66	20.21
P	HE Golubic	7.5	19.94	30.35
P	mHE Krcic	0.375	1.04	31.66
P	HE Miljacka	19.2	77.88	46.30
P	HE Jaruga	7.2	26.46	41.95
A	HE Peruca	61.4	136.98	25.47
A	HE Orlovac	237	414.48	19.96
A	HE Dale	40.8	142.98	40.00
P	HE Kraljevac	46.4	65.84	16.20
A	HE Zakucac	576	1649.12	32.68
A	HE Dubrovnik	126	686.68	62.21
A	HE Zavrelje	2	5.73	32.68

Table 3. Accumulation capacity of HPP in CES

River	*Accumulation*	*Capacity (million m^3)*	*h of operation at nominal power*
Drava	Varazdin	2.80	1.56
Drava	Cakovec	10.50	5.83
Drava	Dubrava	16.60	9.22
Drava	TOTAL river	29.90	
Trebisnjica	Bileca	9.30	57.41
Zrmanja	Stikada	13.65	63.19
Zrmanja	Razovac	1.84	12.78
Cetina	Peruca	543.00	1256.94
Cetina	Busko blato	782.00	3103.17
Cetina	Dale	3.70	4.67
Cetina	Prancevici	6.80	8.59
Cetina	TOTAL river	1335.50	
Rjecina	Valici	0.60	7.94
Lokvarka/Lokve	Bajer	40.59	675.20
Gacka/Lika	Kruscica	128.00	592.59
Gacka/Lika	Sklope	142.00	876.54
Gacka/Lika	TOTAL river	270.00	
Dobra/Mreznica	Lesce	25.70	59.49

Hydrology of the rivers and river basins. River hydrology is necessary to determine the proper dynamics of inflow and for assessing the proper capacities for a certain river flow. The data acquired for this case is provided online by the National Hydro-Meteorological Department (DHMZ) [49]. The format is given as hourly average of flow in m^3/s. Most of the measurements extend in a time period 1947-2013, and are averaged statistically to provide a single representative year of flow as input for the model. Some of the measurement stations have been combined to provide a full account of all the tributaries in cases where it is not possible to obtain measurements from downstream stations. A composite hydrology of all rivers is presented in Figure 7.

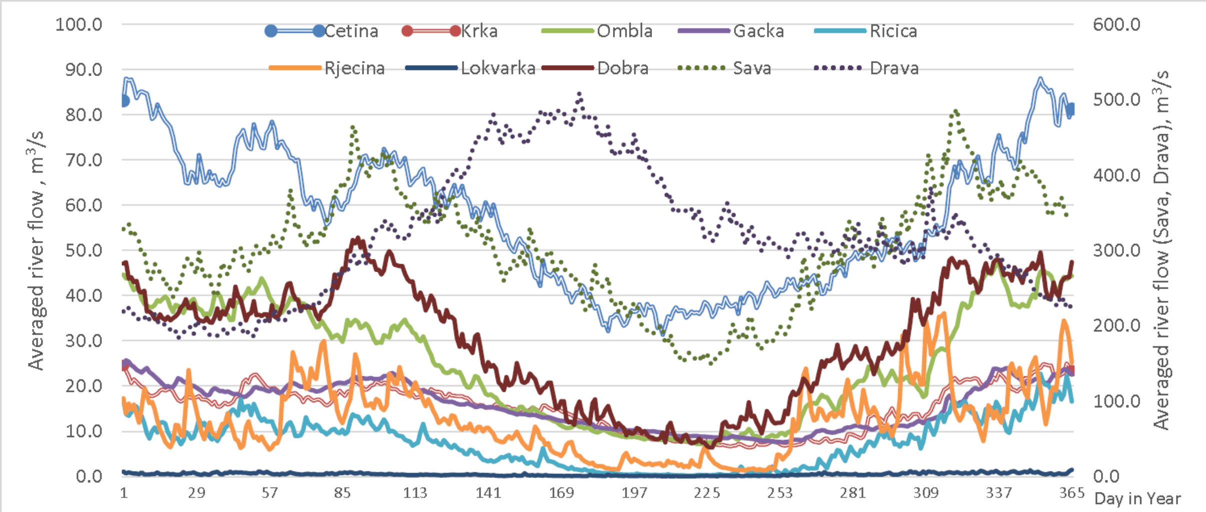

Figure 7. Aggregated flow for all rivers used in CES

Significant differences can be found between rivers. For example, the larger continental rivers Sava and Drava, belonging to the Black Sea basin,have much higher river flow and that why they are shown on secondary Y axis (on the right side) using dotted line style. Those rivers have much more stable average flows during the year, therefore making it more suitable for run-of-river installations. On the other hand, rivers of the Adriatic Sea basin, like Cetina and Krka, are characterised by the high seasonality in flow volumes, due to the carst geography and accentuated by the sudden inflow of either large volume of rain or melting of the snow in the adjacent mountains. Aggregated river flow for the Cetina and Krka are given are shown with double line style and circles at ends, due to their important role in CES. In the summer, prolonged periods of low precipitation lead almost to drying up of the river beds. Central and Western Croatia's rivers such as Rjecina and Dobra exhibit also increased seasonality due to precipitation, with an added difficulty of having very low volume of flow in total.

3.4 RES model in CES

Other RES inputs for the model and the national case include wind and solar resources. All data was acquired from Meteonorm software for six locations: Osijek, Zagreb, Rijeka, Sibenik, Split, Dubrovnik.The parameters from Meteonorm database were: FF – wind speed [m/s]. The raw data was used as an input for wind power production data and converted to wind power potential at 100 m height, G_T – Global radiation tilted [W/m^2], G_H – Global radiation horizontal [W/m^2]

The horizontal radiation data was used to define solar power potential with data from the tilted radiation for verification. It was assumed 135 W/m^2 is the nominal output of 1 m^2 of PV panels.

3.5 Economic model and data

All investment, operation and maintenance, fixed and variable production costs, as well as fuel costs for the model were acquired from the SETIS calculator, a free tool on the European Commission website [50].

Market prices for simulation of import/export were obtained from European Energy Exchange (EEX) [51] in the time period of 2000-2006, which are scaled to an average of 45 EUR/MWh, representing current levels of electricity prices in the European system.

Additionally, for all the data in the study, an average inflation rate of 3.5% was considered and discount rate was set to 8% for all installations. For payment periods of new installations, a 20-year period was assumed for new RES installations, and 30 years for new capital objects, such as TPP or HPP.

For existing installations, almost all capital objects have been paid off, except for a smaller part of TPP Plomin 2 (built 2000) and HPP Lesce (2010). The significance of their share in the overall CES in terms of capital investment was too small to consider assigning current capital value, therefore only the residual value is regarded. That is why installation costs for those power plants are not considered in the model. This is the reason why the solutions in the previously presented regional case study, which takes all installation costs into account, have much higher $\overline{NPV}$.

For RES installations, the current fleet is on average 4-5 years old, and as is regarded as not paid off in total. Again, a 3.5% inflation rate was assumed for all values obtained from SETIS.

3.6 Phase-in and phase-out of capital energy objects in CES up to 2050

As a vast majority of CES capital objects has been built well over 20 years ago, a detailed plan of phasing-out has been given, as according to the plans of the generating operator and given knowledge of technical feasibility of revitalization and modernization. The list phase-out of TPP is given in Table 4. After 2030, around 120 MW of installed TPP only in TPP-DH will remain active. All TPP-Conventional plants will either shutdown or convert to a combined-cycle generation. Note that none of HPP is slated for phase-out, only for revitalization at regular intervals.

The phase-in plan calls for between 192 and 928 MW of new or refurbished HPP capacity until 2035, with 500 MW of coal TPP and 1500 MW of gas TPP. New TPPs are meant to replace existing conventional TPPs with a combined-cycle gas-fired setup, phasing out conventional-cycle gas and oil-fired installations. A single coal TPP of 500 MW is stated for commissioning in 2020.

Table 4. Decommission timetable for existing generators

Decommission	***MW***	***time***	***Decommission***	***MW***	***time***
EL-TO Zagreb A	12.5	2011	TE-TO Osijek A	45	2019
TE Sisak A	210	2013	TE Sisak B	210	2019
TE Plomin A	105	2015	EL-TO Zagreb B	32	2019
TE-TO Osijek A	25	2017	TE Rijeka	320	2020
TE-TO Osijek B	25	2017	EL-TO Zagreb A	25.6	2025
KTE Jertovec A	42.5	2018	EL-TO Zagreb B	25.6	2025
KTE Jertovec B	42.5	2018	TE-TO Zagreb K	210	2030
TE-TO Zagreb C	110	2019	NPP Krsko	348	2043

Special case for consideration is NPP. Sole installation of that is NPP Krsko, built in 1983 and recently given approval for extended operation until 2043. The price of electricity from NPP is given at 45 EUR/MWh fixed until 2023, the end of regular operation, and 65 EUR/MWh fixed in the period 2023-2043, reflecting enhanced investment in security and maintenance.

3.7 EVs in Croatian Energy System

The long-term predictions of number of EVs in the system are based on the study given in [28]. Based on those data, the approximate years of Entry-Into-System (EIS) for pure EV that can work in V2G mode are given in Figure 8.

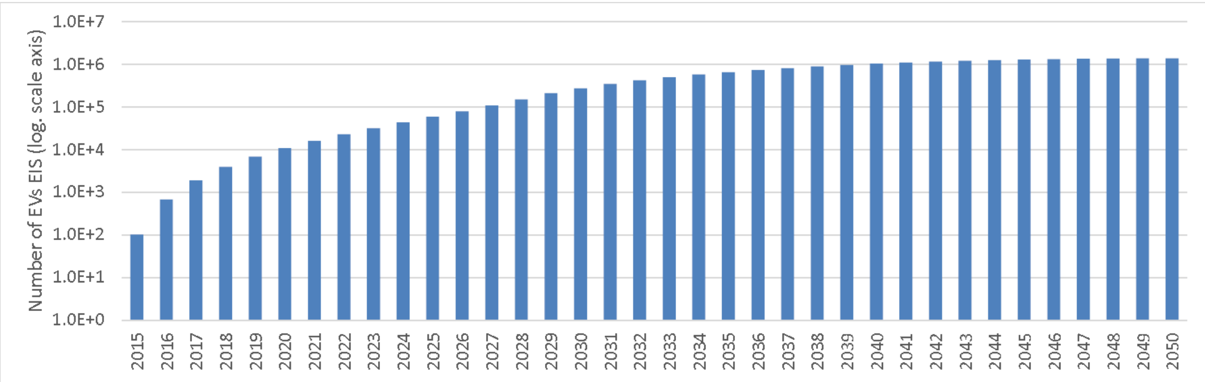

Figure 8. Estimated EVs EIS in CES

Battery capacity of EVs has been determined by an overview of average capacities of available models (see [33] for details), with the mean value of 21 kWh, which was increased to 24 kWh for the purpose of the scenario, as the trend in EV battery capacity shows a clear increase in newer generations of EVs. 24 kWh battery is currently the highest capacity battery for an EV on the market, disregarding the Tesla Model S type (60-85 kWh) and newly introduced Toyota RAV EV 2014 model (41 kWh).

Concerning the available capacity of batteries available for V2G operations, two assumptions are proposed. First one is regarding the amount of EVs actually using the feature of V2G. This option would require some sort of a binding contract with the utility serving the specific area or specific charging points. The second envisions a feature of what amount of capacity left over after the driving cycle are the owners willing to commit for V2G operations. The figures are assumed to be 50% of all owners and 50% of available capacity committed to V2G. Therefore, no more than 25% of the entire fleet's available battery capacity is ever committed to V2G in any given hour.

Final parameters for V2G operation are dedicated to number of vehicles, in time and space coordinates. The options are:

- Driven
- Parked
- Parked & Connected

The driven percentage can be determined by the driving cycle. The ratio between parked and parked with a connection is determined on an hourly time scale for one day, with no distinction between workday and weekend (see Figure 9). This differs from the approach of EnergyPLAN, which uses a defined daily curve for the distribution. It was decided to approach it in this way to add flexibility for various scenarios. The hourly values of EVs at disposal for V2G are as follows: 95% from 0 to 5h, 70% from 6 to 7h, 50% from 8 to 15h, 70% from 16 to 17h and 90% from 18 to 23h.

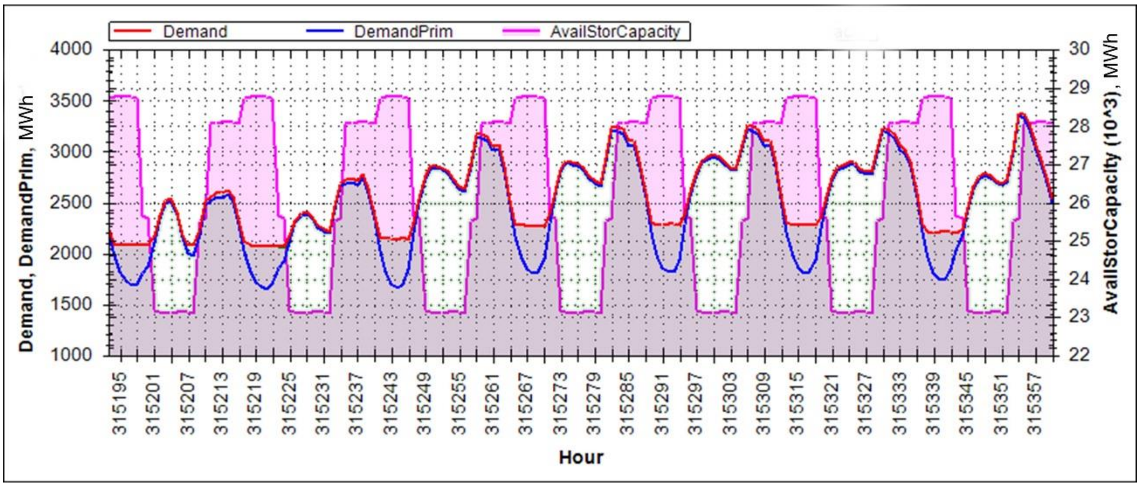

Figure 9. H2RES modelled of primary electrical demand, total demand with energy for EV transport, and available capacity for use in energy system

3.8 CES long-term design optimization problem

Optimization problem formulation for CES long-term design is given by equations (3) and (4). Identified design variables in CES optimization problems are presented in Table 5 together with their bounds. It can be seen that only regulation variables are present for currently available power plants, while the year increase of nominal power is the variable for wind and solar power plants in the main regions in Croatia. Only one new conventional power plant (Gas with district heating) is set for the variable, as explained above. The first block is scheduled for the year 2025 with 5 years update interval for the building of additional blocks.

In this study only SPP and WPP were treated as renewable energy sources (RES), while HPP are included in renewable sources (RwHES) only for specific purposes.

Table 5. Design variables in CES optimization problems

Powerplant	Storage	Name	P_{Ni}		ΔP_i			$s_{lc,j}$		$r_{i,t}$	
i	j		lower	upper	lower	upper	(u_i)	lower	upper	lower	upper
1		HES Drava	-	-	-	-	-	-	-	0	1
2		HES Dubrovnik	-	-	-	-	-	-	-	0	1
3		HES Krka	-	-	-	-	-	-	-	0	1
4		HES Cetina	-	-	-	-	-	-	-	0	1
5		HE Rijeka	-	-	-	-	-	-	-	0	1
6		HES Vinodol	-	-	-	-	-	-	-	0	1
7		HES Senj	-	-	-	-	-	-	-	0	1
8		HES Dobra	-	-	-	-	-	-	-	0	1
9		HES Sava	-	-	-	-	-	-	-	0	1
10		HE Ombla	-	-	-	-	-	-	-	0	1
11		TPP Gas	-	-	-	-	-	-	-	0.1-0.3	1
12		TPP Gas-DHOld	-	-	-	-	-	-	-	0.1-0.3	1
13		TPP Coal	-	-	-	-	-	-	-	0.3	1
14		NPP Krsko	-	-	-	-	-	-	-	1	1
15		WPP Sibenik	-	-	1	10	1	-	-	/	/
16		WPP Rijeka	-	-	1	10	1	-	-	/	/
17		WPP Split	-	-	1	10	1	-	-	/	/
18		WPP Dubrovnik	-	-	1	10	1	-	-	/	/
19		WPP Zagreb	5	50	1	10	1	-	-	/	/
20		WPP Osijek	5	50	1	10	1	-	-	/	/
21		SPP Sibenik	-	-	1	20	1	-	-	/	/
22		SPP Rijeka	-	-	1	20	1	-	-	/	/
23		SPP Split	-	-	1	20	1	-	-	/	/
24		SPP Dubrovnik	-	-	1	20	1	-	-	/	/
25		SPP Zagreb	1	20	1	20	1	-	-	/	/
26		SPP Osijek	1	20	1	20	1	-	-	/	/
27		TPP Gas-DHNew (*short name* Gas)	100	600	10	100	5	-	-	0.1-0.3	1
28	1	EVs	-	-	-	-	-	80	99	-1	1
29	2	Rev Hydro	-	-	-	-	-	70	99	-1	1

4 RESULTS AND DISCUSSION

The following figures present obtained non-dominated solutions for Global problems displayed in *DeMak* graphical interface. The first figure (Figure 10) display Pareto solutions in attribute/objective space where the three used objectives, min *NPV*, min $\overline{NPV}$ (NPV_e in graphs), max *RESSh* are on *x y z* coordinate axis. In order to help the reader to position presented solutions in 3D space, the figures also show projections of those solutions on 2D planes (in black). Ideal design (utopia) is also shown in Figure 10 (large sphere in upper left corner) for the reference purpose. Since the figure represents the Pareto frontier, the best value according to each objective is on one of the edges of attribute space and satisfaction for each objective monotonously decreases with distance from the relevant edge. It is evident that any of the objectives cannot be improved without being worsened in another. That why this figure gives energy system design decision makers the best insight in the cost of incorporating more RES sources in particular energy system. Figure 10 also identifies two designs, design A and design B, which will be analysed in detail later in this chapter.

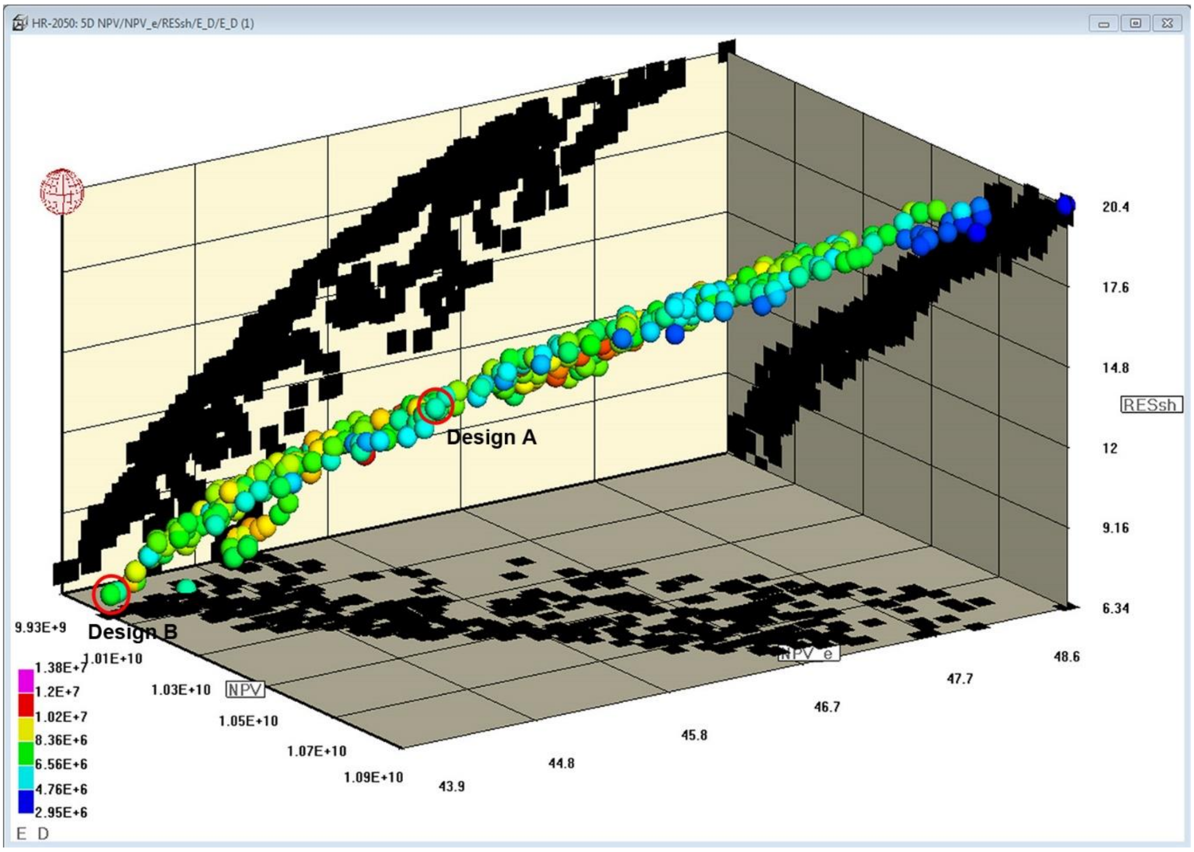

Figure 10. *Non-dominated solutions in attribute space (*$\overline{NPV}$*, NPV and RESSh)*

Figure 11. shows interesting, yet expected characteristics that variants with higher share of conventional power sources still produces more expensive energy ($\overline{NPV}$). Although variable expenses are much smaller for RES, investment cost is still much higher and plays dominant role.

Another interesting aspect of obtained non-dominated solutions is the relation between RES share, total installed nominal power of new Gas power plant with district heating and its load factor (see Figure 12.). It is evident that nominal power and its load factor decreases as the share of RES increase. However, certain level of nominal power always needs to be in the system to cover bed weather conditions (cloudy days without wind), and to cover heating demand.

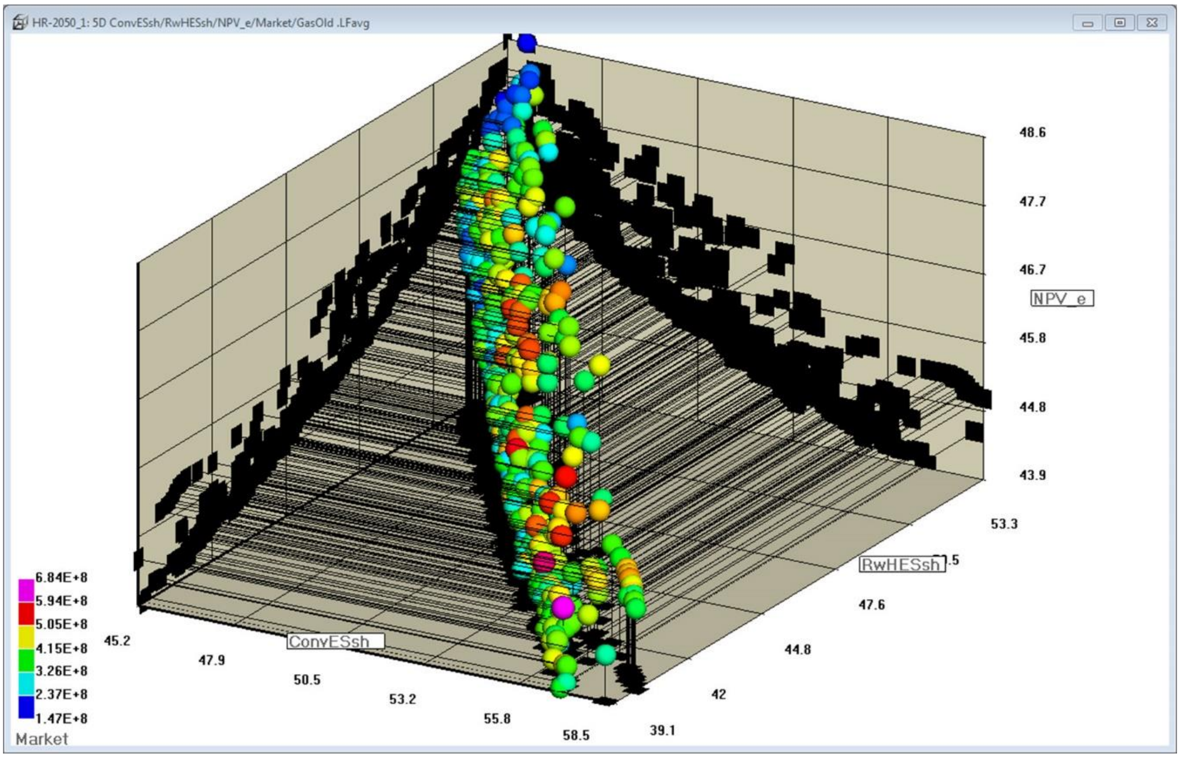

Figure 11. Relation between $\overline{NPV}$ and ratios of energy produced by conventional and renewable power sources

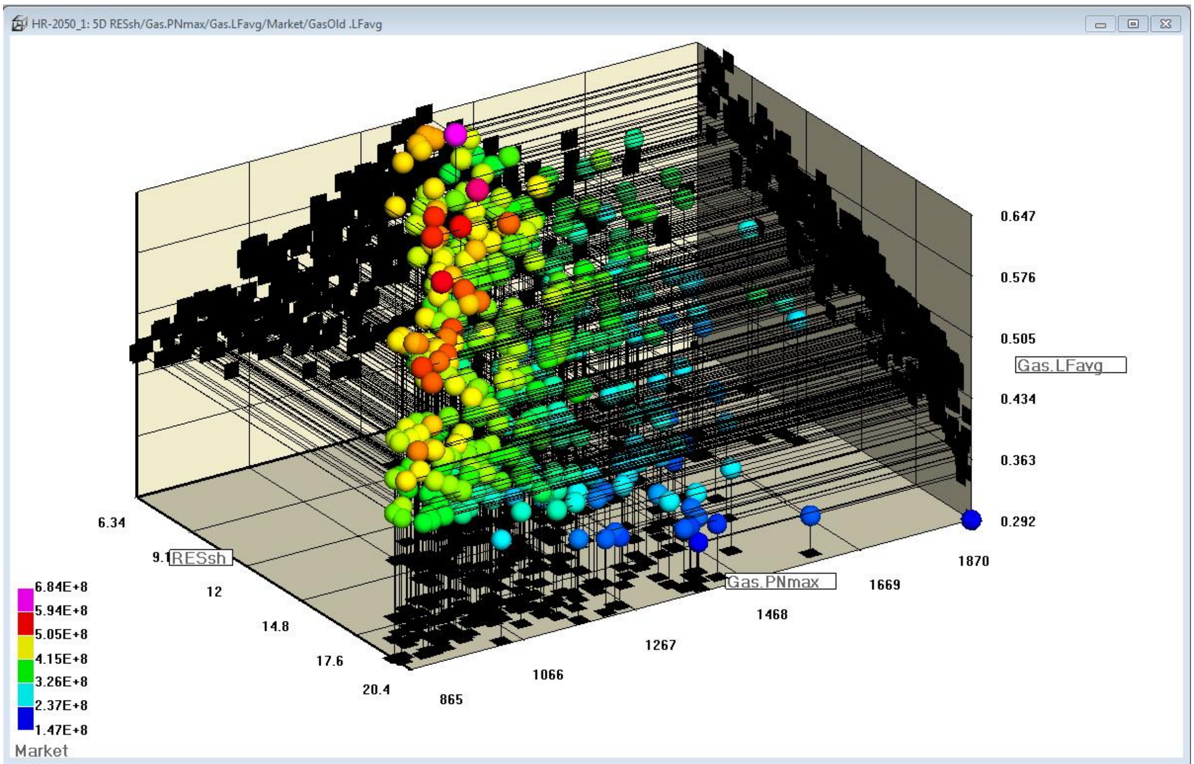

Figure 12. Relation between RES share, total installed nominal power of new Gas power plant with district heating and its load factor

4.1 Analysis of the two proposed energy system design variants

As have already been mentioned, two selected designs that will be used for the further study are identified in Figure 10. Design B is the variant of national energy system with the lowest value of $\overline{NPV}$, while design A is energy system with almost doubled RES share compared with design B, and some (arguably) reasonable $\overline{NPV}$. More details on two selected designs are given in Table 6.

Figure 13. presents Design A cumulative total electricity Demand and cumulative produced energy for each year in 36 years-long scenario, together with cumulative Primary Electricity Demand, which does not include demand for charging of EVs for their transportation needs. On the left y axis is the cost of the electricity purchased on the market. The largest gap between produced electricity and demand is between fifth and tenth year of scenario due to decommission of several conventional power plants (see Table 4). One smaller gap is between 28^{th} and 29^{th} year of scenario due to decommissioning of NPP Krsko as identified in Figure 14. The same figures also presents cumulative produced energy of the new Gas TPP with district heating, which adds a new block each five years (the last in the 29^{th} year of scenario). For comparison, Figure 15. and Figure 16. present the same outputs for Design B. The only visible difference is a slightly higher price of energy purchased on the market in the last part of the scenario. It is interesting to notice that Design B install 175 MW more nominal power in the new Gas TPP than Design A, while having a 20% higher load factor (see Table 6). The reason for that probably lies in the fact that Design A still needs to cover unfavourable weather conditions and heating demand. That is the reason why the load factor of combined-cycle gas TPP is much smaller for Design A.

Some additional interesting aspects of Design A are shown in the next several figures. Figure 17. illustrates how electrical energy stored in EV helps to cover increased demand in the first and third quarter of the last year. This is especially useful in the third quarter when HPP produce less energy due to smaller water inflow during summer.

Table 6. *The main characteristics of designs A and B*

Optimization Component	A	B
Gas.PN (MW)	260	395
Gas.PndY (MW)	52	54
WPP Sibenik.PNdY (MW)	9	8
WPP Rijeka.PNdY (MW)	2	1
WPP Split.PNdY (MW)	10	4
WPP Dubrovnik.PNdY (MW)	9	4
WPP Zagreb.PN (MW)	22	18
WPP Zagreb.PNdY (MW)	1	1
WPP Osijek.PN (MW)	20	13
WPP Osijek.PNdY (MW)	4	1
SPP Sibenik.PNdY (MW)	16	1
SPP Rijeka.PNdY (MW)	14	1
SPP Split.PNdY (MW)	16	1
SPP Dubrovnik.PNdY (MW)	10	1
SPP Zagreb.PN (MW)	5	1
SPP Zagreb.PNdY (MW)	12	8
SPP Osijek.PN (MW)	15	1
SPP Osijek.PNdY (MW)	8	1
Rev-OpLev (%)	77	72
EV-OpLev (%)	86	88
NPV (EUR)	10.4E+9	10.1E+9
NPV_e (EUR/MWh)	45.35	43.9
RESsh (%)	14.6	7.07
RwHESsh (%)	46.64	39.34
ConvESsh (%)	49.85	56.83
EE (MWh)	12343	1546
E_D (MWh)	5656516	7041469
Market (EUR)	283E+06	350E+06
MaxPN (MW)	8403	6061
EndPN (MW)	8403	6061
MinLF (relative)	0.329	0.3408
MaxLF (relative)	0.4868	0.4881
AvgLF (relative)	0.3622	0.371
EndLF (relative)	0.329	0.341
Gas.Pnmax (MW)	1300	1475
Gas.Lfavg (relative)	0.4824	0.5813

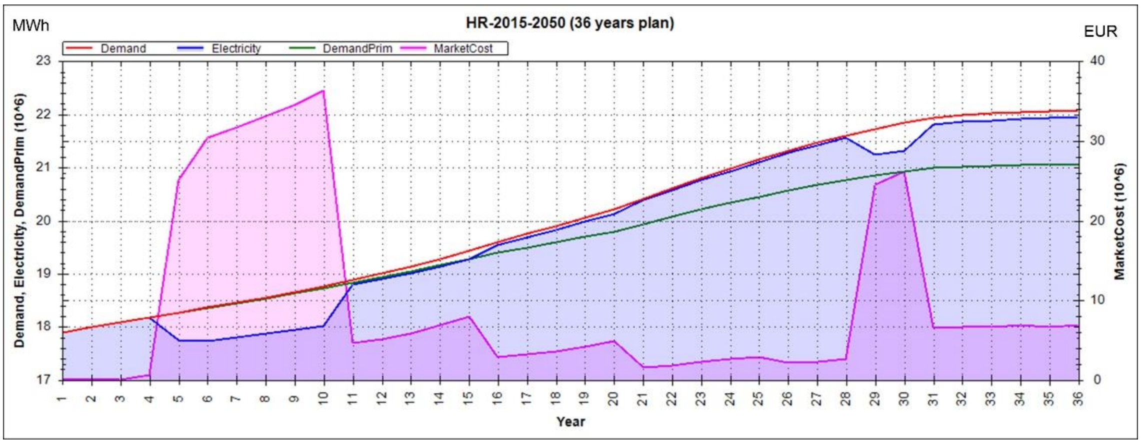

Figure 13. Design A – Cumulative Primary and Total Demand, Produced and Purchased Electrical Energy

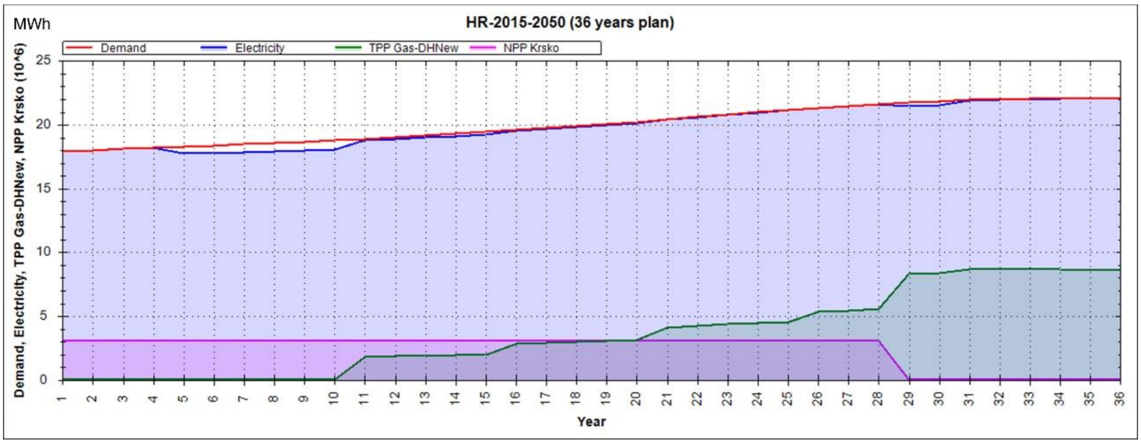

Figure 14. Design A – Cumulative Primary and Total Demand, NPP Krsko and new DH GAS Powerplant

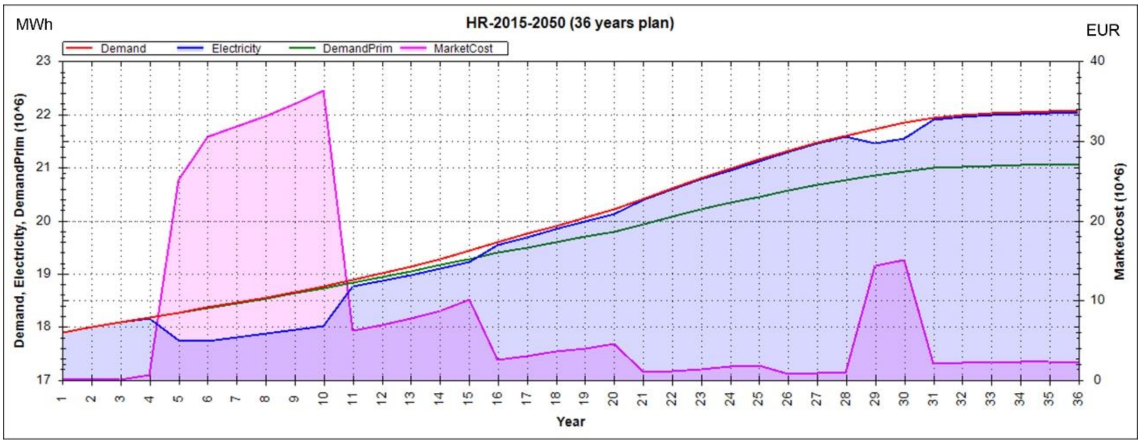

Figure 15. Design B – Cumulative Primary and Total Demand, Produced and Purchased Electrical Energy

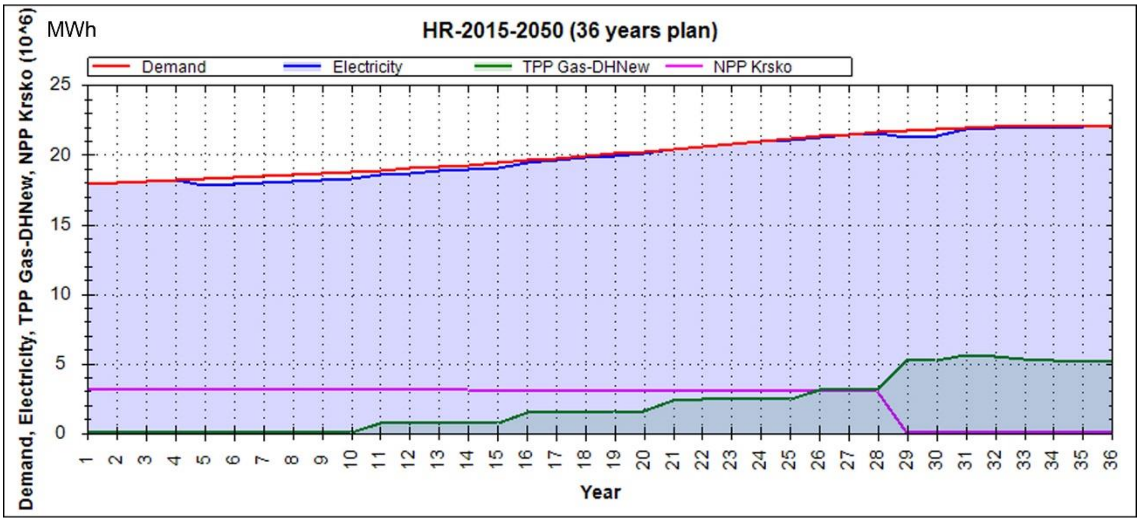

Figure 16. Design B - Cumulative Primary and Total Demand, NPP Krsko and new DH GAS Powerplant

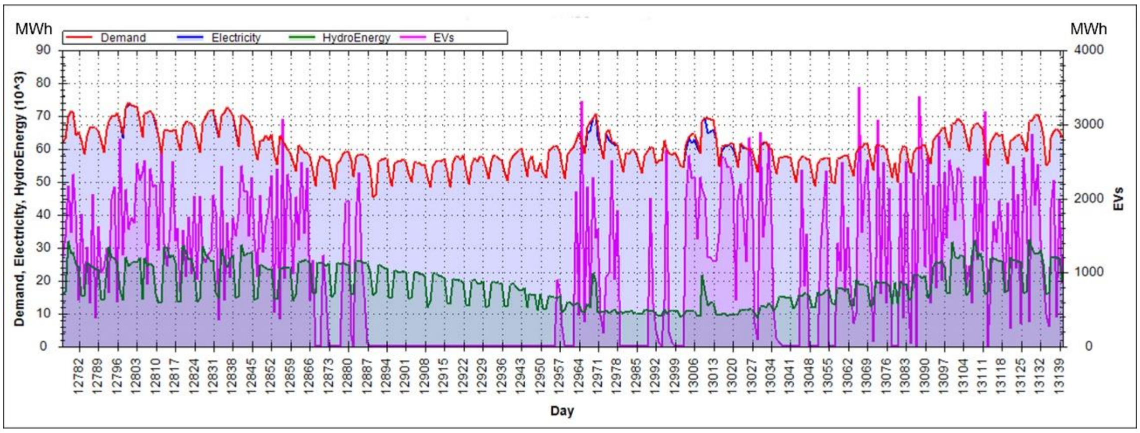

Figure 17. Design A – Last year Cumulative Demand, Total Electrical Energy, Hydro and EV Energy

Figure 18. shows production of the largest aggregated HPP in the scenario – HES Cetina. This aggregated HPP also has the largest accumulation. The figure shows how water aggregated during the rainy season is kept for the summer. However, since during the summer season the two highest energy demand peaks exist, HPP does not have enough accumulated water to produce satisfactory amount of electricity, as it does in the first quarter when sufficient amount of water exists. Magnified detail in Figure 18. shows how those inadequacies in hour production during the critical week in summer are supplemented from the market.

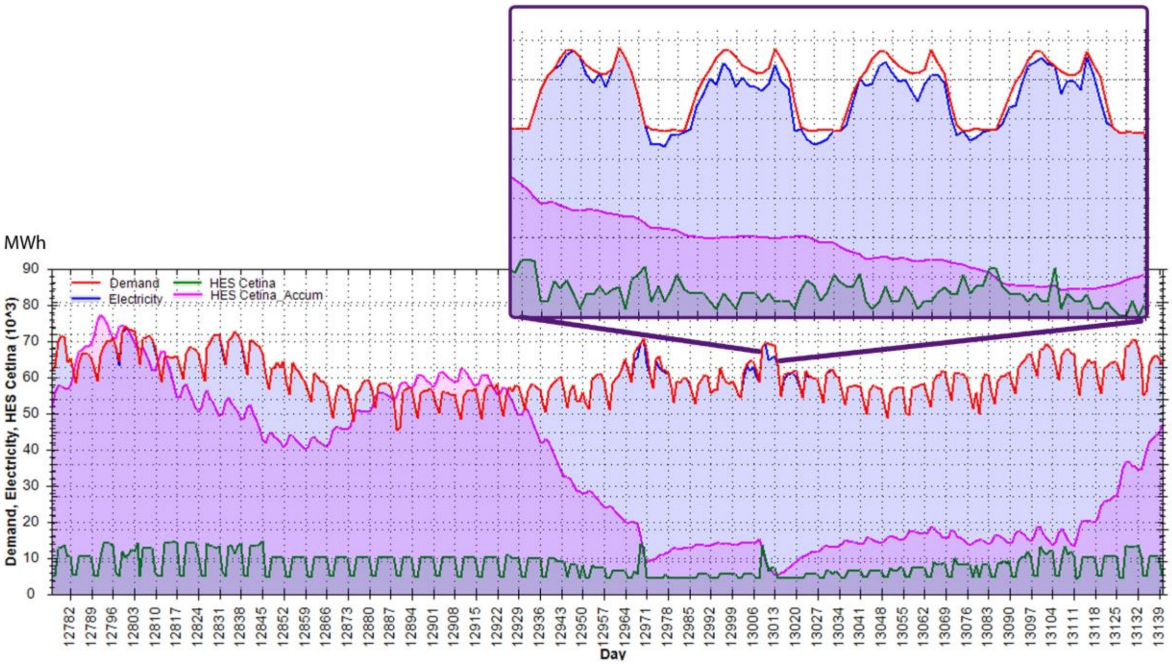

Figure 18. Design A – Last year Cumulative Demand, Total Electrical Energy, Hydro Energy and Accumulation

5 CONCLUSION

Comprehensive CES long-term design is presented as one of the results of three year national research project iRESEV. The project has enabled collection of various sources of data that are necessary for preparation of national energy system model, such as transportation system, meteorological data for solar insulation and wind characteristics in several regions, hydrology of river basins, heating and cooling demand, etc.

Two-level energy system design problem formulation which is presented in this paper enables generation of Pareto front even for an energy system of significant size, with more than thirty individual components. Possibility of generation of Pareto front with relevant objectives gives deeper insight on energy system characteristics to the designer of an energy system as shown in the discussion on obtained results of national case study.

The results of national case study suggests that, if there will be no initiatives for the development of a new technologies or energy storage systems, certain level of conventional energy sources will have to remain in the energy system to cover unfavourable weather conditions and to cover heating demand. Also, variants with more RES share have lower total energy system load factor and significantly higher installed capacity.

EVs, as seen from the case study, do not have only negative impacts on the energy system, in terms of consumption, while having a positive influence by discharging energy into the system in times of peak demand. Total cost of the system can be brought down by utilizing periods of low demand to shift vehicle charging (usually night time), thereby keeping peak demand values as they are. In that way EV's can reduce the total energy system nominal power installation and/or enable better control on the periods of buying the energy from the market thus avoiding the periods with the peek high price on the market. The mentioned can only be achieved through V2G operation that demands different pricing system than currently is in Croatia. Also, the current two-tariff pricing in Croatia is unsustainable, as without regulation charging, the peak demand value would surge by almost 6 GW. However it is the opinion of the authors that those issues can be solved before expected significant penetration of EVs in third decade of this century.

Future work could include further steps in validation of the long-term energy system planning model which was developed during this project. Additionally, some method for securing of energy supply could be implemented in the model in order to obtain more realistic energy system behaviour. Heat and cold energy storage on a district level or an interconnections to other national systems could also be elaborated better and included in the model. The proposed problem solutions suggested in the regional and national case studies should be further investigated and improved regarding the efficiency and stability of the solutions. One of the important goals is accommodation of mathematical model for parallelization in order to exploit multi-processor/multi-core capabilities of today's computers.

Regarding the national case study modelling, data inputs for meteorological and hydrology time series should be further adapted and analysed statistically, especially in the area of hydrology concerning river basins shared with neighbouring states (Bosnia and Hercegovina, Slovenia, and to some extent Serbia and Hungary). Also the model could include the sHPP, which are not considered here, since some of the recent studies from EIHP suggest that Croatia still has potential for ~200 MW or ~550 GWh/year in that field. Biomass and biogas TPP are also under consideration for modelling as a valuable addition economic multiplier to the power sector, taking in a large amount of biomass otherwise exported or wasted.

ACKNOWLEDGMENTS

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REFERENCES

1. International Energy Agency. Energy and climate change (2015) World Energy Outlook Special Report OECD/IEA
2. International Energy Agency. Energy Technology Perspectives 2015 - Mobilising Innovation to Accelerate Climate Action. (2015)
3. D. Connolly, H. Lund, B. V. V. Mathiesen, and M. Leahy, “A review of computer tools for analysing the integration of renewable energy into various energy systems,” Appl. Energy, vol. 87, no. 4, pp. 1059–1082, Apr. 2010.
4. Østergaard, P.A. Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations, Applied Energy, Vol. 154, 921-933 10.1016/j.apenergy.2015.05.086, 2015.
5. H. Lund and E. Münster, “Modelling of energy systems with a high percentage of CHP and wind power,” Renew. Energy, vol. 28, no. 14, pp. 2179–2193, Nov. 2003.
6. H. Lund, P. A. Østergaard, and I. Stadler, “Towards 100% renewable energy systems,” Appl. Energy, vol. 88, no. 2, pp. 419–421, Feb. 2011.
7. H. Lund and B. V. Mathiesen, “Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050,” Energy, vol. 34, no. 5, pp. 524–531, 2009.
8. G. Gasparovic, G. Krajacic, N. Duic, and M. Baotic, 24th European Symposium on Computer Aided Process Engineering, vol. 33. Elsevier, 2014.
9. G. Krajacic, R. Martins, A. Busuttil, N. Duic, and M. da G. Carvalho, “Hydrogen as an energy vector in the islands’ energy supply,” Int. J. Hydrogen Energy, vol. 33, no. 4, pp. 1091–1103, Feb. 2008.

10. R. Segurado, G. Krajacic, N. Duic, and L. Alves, "Increasing the penetration of renewable energy resources in S. Vicente, Cape Verde," Appl. Energy, vol. 88, no. 2, pp. 466–472, Feb. 2011.
11. G. Krajacic, N. Duic, and M. da G. Carvalho, "H2RES, Energy planning tool for island energy systems – The case of the Island of Mljet," Int. J. Hydrogen Energy, vol. 34, no. 16, pp. 7015–7026, Aug. 2009.
12. N. Duic´, Z. Guzovic´, V. Kafarov, J. J. Klemes, B. vad Mathiessen, J. Yan, K. Suomalainen, C. Silva, P. Ferrão, and S. Connors, "Wind power design in isolated energy systems: Impacts of daily wind patterns," Appl. Energy, vol. 101, pp. 533–540, 2013.
13. Wierzbowski, M., Lyzwa, W., Musial, I., MILP model for long-term energy mix planning with consideration of power system reserves, Applied Energy, Vol. 169, pp. 93-111, 10.1016/j.apenergy.2016.02.003, 2016
14. N. Duic, G. Krajacic, and M. da G. Carvalho, "RenewIslands methodology for sustainable energy and resource planning for islands," Renew. Sustain. Energy Rev., vol. 12, no. 4, pp. 1032–1062, May 2008.
15. F. Chen, N. Duic, L. Manuel Alves, and M. da Graça Carvalho, "Renewislands—Renewable energy solutions for islands," Renew. Sustain. Energy Rev., vol. 11, no. 8, pp. 1888–1902, Oct. 2007.
16. Z. Bacelic Medic, B. Cosic, and N. Duić, "Sustainability of remote communities: 100% renewable island of Hvar," J. Renew. Sustain. Energy, vol. 5, no. 4, p. 041806, Jul. 2013.
17. P. Petruschke, G. Gasparovic, P. Voll, G. Krajacic, N. Duic, and A. Bardow, "A hybrid approach for the efficient synthesis of renewable energy systems," Appl. Energy, Apr. 2014.
18. M. Manfren, P. Caputo, and G. Costa, "Paradigm shift in urban energy systems through distributed generation: Methods and models," Appl. Energy, vol. 88, no. 4, pp. 1032–1048, 2011.
19. Q. Zhang, B. C. Mclellan, T. Tezuka, and K. N. Ishihara, "An integrated model for long-term power generation planning toward future smart electricity systems," Appl. Energy, vol. 112, pp. 1424–1437, Dec. 2013.
20. Flores, J.R., Montagna, J.M., Vecchietti, A. An optimization approach for long term investments planning in energy, Applied Energy, 122, pp. 162-178, 2014. DOI: 10.1016/j.apenergy.2014.02.002

21. C. Bussar, M. Moos, R. Alvarez, P. Wolf, T. Thien, H. Chen, Z. Cai, M. Leuthold, D. U. Sauer, and A. Moser, "Optimal Allocation and Capacity of Energy Storage Systems in a Future European Power System with 100% Renewable Energy Generation," Energy Procedia, vol. 46, pp. 40–47, 2014.
22. I. Pawel, "The cost of storage - How to calculate the levelized cost of stored energy (LCOE) and applications to renewable energy generation," Energy Procedia, vol. 46, pp. 68–77, 2014.

23. Etxeberria, I. Vechiu, H. Camblong, and J. M. Vinassa, “Comparison of three topologies and controls of a hybrid energy storage system for microgrids,” Energy Convers. Manag., vol. 54, no. 1, pp. 113–121, Feb. 2012.
24. Koltsaklis, N.E., Georgiadis, M.C. A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints, Applied Energy, 158, pp. 310-331, 2015. DOI: 10.1016/j.apenergy.2015.08.054
25. M. Stadler, C. Marnay, R. Sharma, G. Mendes, M. Kloess, G. Cardoso, O. Megel, and a. Siddiqui, “Modeling electric vehicle benefits connected to smart grids,” in 2011 IEEE Vehicle Power and Propulsion Conference, VPPC 2011, 2011, pp. 1–8.
26. K. Clement-Nyns, E. Haesen, and J. Driesen, “The impact of vehicle-to-grid on the distribution grid,” Electr. Power Syst. Res., vol. 81, no. 1, pp. 185–192, Jan. 2011.
27. H. Lund and W. Kempton, “Integration of renewable energy into the transport and electricity sectors through V2G,” Energy Policy, vol. 36, no. 9, pp. 3578–3587, Sep. 2008.
28. T. Puksec, G. Krajacic, Z. Lulic, B. V. Mathiesen, and N. Duic, “Forecasting long-term energy demand of Croatian transport sector,” Energy, vol. 57, no. null, pp. 169–176, Aug. 2013.
29. Connolly, D., Mathiesen, B. V. (2014). A technical and economic analysis of one potential pathway to a 100% renewable energy system. International Journal of Sustainable Energy Planning and Management, 1, 7-28. 10.5278/ijsepm.2014.1.2
30. B.V. Mathiesen, H. Lund, D. Connolly, H. Wenzel, P.A. Ostergaard, B. Möller, S. Nielsen, I. Ridjan, P. Karnoe, K. Sperling, F.K. Hvelplund. Smart Energy Systems for coherent 100% renewable energy and transport solutions. Applied Energy (145), 139-154.
31. L.T. Biegler., I.E. Grossmann. Retrospective on optimization. Computers and Chemical Engineering 28 (2004) 1169-1192
32. L.T. Biegler., I.E. Grossmann. Part II. Future perspective on optimization. Computers and Chemical Engineering 28 (2004) 1193-1218
33. G. Gasparovic, P. Prebeg, G. Krajacic and N. Duic, “Multi-objective long-term optimization of energy systems with high share of renewable energy resources.” SDEWES 2014, Ohrid.
34. S. Obara and S. Watanabe, “Optimization of equipment capacity and an operational method based on cost analysis of a fuel cell microgrid,” Int. J. Hydrogen Energy, vol. 37, no. 9, pp. 7814–7830, May 2012.
35. M. G. Ippolito, M. L. Di Silvestre, E. Riva Sanseverino, G. Zizzo, and G. Graditi, “Multi-objective optimized management of electrical energy storage systems in an islanded network with renewable energy sources under different design scenarios,” Energy, vol. 64, pp. 648–662, Jan. 2014.
36. S. Sinha and S. S. Chandel, “Review of software tools for hybrid renewable energy systems,” Renew. Sustain. Energy Rev., vol. 32, pp. 192–205, Apr. 2014.
37. A. T. D. Perera, R. A. Attalage, K. K. C. K. Perera, and V. P. C. Dassanayake, “A hybrid tool to combine multi-objective optimization and multi-criterion decision making in designing standalone hybrid energy systems,” Appl. Energy, vol. 107, pp. 412–425, Jul. 2013.

38. P. Prebeg, V. Zanic, and B. Vazic, “Application of a surrogate modeling to the ship structural design,” Ocean Eng., vol. 84, pp. 259–272, Jul. 2014.
39. V. Zanic, J. Andric, P. Prebeg, and P. Zanic, V.; Andric, J.; Prebeg, “Design synthesis of complex ship structures,” Ships Offshore Struct., vol. 8, no. 3–4, pp. 383–403, Jun. 2013.
40. P. A. Østergaard, “Reviewing optimisation criteria for energy systems analyses of renewable energy integration,” Energy, vol. 34, no. 9, pp. 1236–1245, Sep. 2009.
41. M. Schulze and G. Gasparovic, “Network Flow Model for Multi-Energy Systems,” EE’10 Proc. 5th IASME/WSEAS Int. Conf. Energy {&} Environ., pp. 172–177, Feb. 2009.
42. P. Voll, M. Lampe, G. Wrobel, and A. Bardow, “Superstructure-free synthesis and optimization of distributed industrial energy supply systems,” Energy, vol. 45, no. 1, pp. 424–435, Sep. 2012.
43. P. Voll, C. Klaffke, M. Hennen, and A. Bardow, “Automated superstructure-based synthesis and optimization of distributed energy supply systems,” Energy, vol. 50, pp. 374–388, Feb. 2013.
44. HEP yearbook 2013 [Online] http://www.hep.hr/hep/publikacije/godisnje/2013godisnje.pdf
45. HEP Power Generation Ltd. http://www.hep.hr/proizvodnja/
46. MINGO-OIEKPP - http://oie.mingo.hr/default.aspx?id=8
47. ENTSO-E - https://www.entsoe.eu/data/data-portal/production/Pages/default.aspx
48. Irsag B., Puksec T., Duic N., Long term energy demand projection and potential for energy savings of Croatian tourism–catering trade sector, *Energy*, Vol. 48, pp 398-405, 2012
49. DHMZ - Hydrology sector - http://161.53.81.21/
50. SETIS Energy Calculator - http://setis.ec.europa.eu/EnergyCalculator/
51. European Energy Exchange EEX - https://www.eex.com/en/