Economic viability of flexibility options for smart energy systems with high penetration of renewable energy

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Abstract

Since the signing of the Paris Climate Agreement, European Union has made contributions to increase the share of renewable energy in its energy mix and limit global warming to 2 °C. Additionally, the European Union has with the passing of the "European Green Deal", set a plan to transition to a carbon-neutral economy by 2050 which is planned to be achieved by the implementation of renewable energy generating capacities and parallel implementation of sector coupling, energy balancing, and storage technologies. These technologies are required to avoid the emergence of new problems like curtailment and jeopardization of system stability. The application of these technologies may vary due to their operating characteristics as well as the costs associated with them. The goal of this research is to show the most economically viable dynamics of achieving high penetration of renewable energy in combination with different flexibility options on a case study. Application of flexibility options is considered with the goal of keeping critical excess electricity generation within 5% of total electricity demand. The simulations are performed with the combination of energy planning software EnergyPLAN and an optimization software EPLANopt.

Results show that the most effective technologies are the vehicle to grid, smart charge, improvements of energy efficiency, and pumped hydro storage.

Keywords: Energy system modelling, EnergyPLAN, Renewable energy integration, Demand response, Decarbonization

Introduction

The "European Green Deal" describes ambitious European goals of reaching carbon neutrality by the year 2050. As a member state of the European Union, the Republic of Croatia adopted common goals in its strategic documents [1]. Croatia has a high penetration of renewable energy sources (RES) in its electricity generation, reaching 68 %, thanks to hydropower and wind power [2]. It can be noted that generation from hydropower varies on an annual basis, because of variations in precipitation and climate conditions. In 2018, renewable variable energy sources such as wind power and PV made up 10.6 % of total electricity generation in Croatia. It should also be noted that Croatia imports about 33 % of the electricity [3]. This is stated as one of the key problems of Croatian energy balances stated in the Energy Strategy of the Republic of Croatia [4], as it strives for an increase in self-sufficiency. An additional problem with the Croatian energy system is the widespread use of fossil fuels in the heating and transport sectors. These sectors, in combination with the power sector, account for 70 % of CO_2 emissions [2]. Croatia possesses significant potential for the implementation of both solar and wind energy, with average solar irradiation of over 1500 kWh/m^2 in the southern part of the country [5]. The coastal part also experiences high average wind speeds, thus making the area suitable for wind power plant utilization [6].

Curtailment of VRES generation

Although wind and solar power offer cheap electrical energy [7], they also cause the appearance of other problems in the energy system. Meha et al. [8] demonstrated problems that can arise in systems with a high share of variable renewable energy sources (VRES). The curtailment of VRES appears when the electricity grid operator opts to limit the output of VRES to preserve the stability of the electricity grid. The problem of energy system instability is based on the equilibrium of demand and generation. If there is a mismatch between these two values, the frequency of electricity will start to change. In the case of too big supply, the frequency will increase while in the case of the demand bigger than supply, the frequency will decrease. In Europe, the native frequency of the electrical grid is 50 Hz [9]. The frequency is kept between 49,5 and 50,5 Hz. In the case of a bigger mismatch between real frequency and 50 Hz, the damage to the equipment and infrastructure will start appearing. The reason for opting for this mode of operation lies in the operating characteristics of the rest of the power system. For example, an inflexible thermal power plant cannot reduce its output sufficiently if the reduction of generation from renewable energy is expected in the next couple of hours. Therefore, it needs to either stay on high output or shut down completely – thus presenting a challenge to the system's stability. An example of this operation can be observed when, during the afternoon, the peak output of solar power plants appears, and a thermal power plant might not be required. The problem manifests itself when the output of solar plants starts to decrease right at the time it coincides with evening peak electricity demand. Therefore, if a thermal power plant is not capable of performing a fast ramp-up procedure to deliver the required electricity generation for evening peak demand, an operator may choose to keep it operating at a reduced power level throughout the day. This, in turn, means that the output from solar power plants may have to be reduced[10]. The problem of inflexible thermal power plants and their inherent limitation on enabling the realization of higher penetration of VRES is examined as well by Cerovac et al. [11] in the case of the Croatian energy system. There are two reasons for the resulting undesirability of an energy system that opts to curtail generation from VRES. The first one is the adherence to the planned share of renewable energy and carbon emission mandates. Therefore, if the output of VRES is limited, an insufficient effect on the share of VRES or carbon emissions may be achieved. This notion ties in with the second problem, which is the aspect of economics. The operation of VRES with regular curtailment may provide the investors with diminishing returns on their investment and increased uncertainty in future generation estimations. This problem is also analysed by O'Shaughnessy et al. [12]. The paper discussed the problems of the systems with high penetration of PV installed and the curtailment caused by the excessive installation of VRES without the introduction of flexibility. The exact extent of the problem may be defined by the structure of an energy market and whether the power generation facility, that is being curtailed, is inside the subsidy system. Additional limitations on the penetration of VRES may come in the form of limited transmission line capacities, as mentioned by Taseska-Gjorgievska et al. [13] in the case of the North Macedonian energy system. The capacities of the power lines, as well as the atmospheric conditions, may inhibit the transfer of energy without irreversible damage to the power lines caused by excessive thermal loads. Therefore, an upgrade of transfer lines is also required.

Problem with biomass

Another point of consideration is the use of biomass. Biomass is considered because it is renewable fuel source. Biomass power plants are dispatchable which makes them ideal in the energy system with high shares of VRES. Also, some of the existing coal power plants can be converted to run on biomass [14]. Biomass is generally considered sustainable if the replenishment rate is equal or greater to the harvesting rate. It is either harvested from existing forests or cultivated. Both of the options come with problems. Direct harvesting comes with a range of environmental problems in the realm of encroaching on and destroying wildlife habitats [15]. An additional problem can be observed when taking a look at the map of forestlands in Europe [16]. As can be seen, a significant portion of the remaining European forestlands are located in Croatia and therefore need to be managed sustainably [17]. Cultivated farming on the other hand is also under criticism from the agricultural land management aspect, where it is seen as competition with food crops [18]. Finally, the biggest problem in using biomass is the thermal efficiency of the processes and the resulting demand for biomass. For example, when coal is replaced with biomass, the consumption of fuel doubles due to it having approximately half of the energy value. Therefore, the biomass should primarily be used in CHP plants where most of the energy is utilized.

The problem of the rapid growth of biomass consumption is examined by Mortensen et al. [19]. The authors argue that the solution to the "biomass bottleneck" problem is in the integration of flexibility options like hydrogen generation. Jensen et al. [20] consider the same problem and come up with synthetic fuels as the solution, so there should be a focus on more widespread integration of hydrogen-based fuels. An additional problem, often most notable in urban areas, is the emission of particulate matter and its related adverse effects on health [21].

The biomass potential of Croatia, as shown in GIS data by Lovrak et al.[22], accounts for up to 6.7 TWh of biogas available on an annual basis, and up to 117 TWh of total bioenergy presented in the Croatian energy strategy [4]. Though Croatia has relatively high available biomass potential when compared to its energy demand, not all of that is considered sustainable [4].

In the end, the use of biomass in a sustainable way is limited to agricultural residues, leftovers from industry, old and dead biomass, and cultivated biomass.

The solution to the problems

The solution to the mentioned problems lies in the implementation of renewable electricity generating technologies in combination with demand response technologies and improvements in various sectors. These include energy refurbishments of buildings, electrification of transport, electrification of heating, and other sector coupling concepts examined by Groppi et al. [23]. The exact capacities and technologies that are to be implemented as well as at what stage of energy system transformation are the subject of local specific conditions. Also, the results may be different when multiple technologies are considered for implementation at the same time. Sector coupling is the idea of interconnecting (integrating) the energy-consuming sectors - buildings (heating and cooling), transport, and industry - with the power-producing sector [24]. Pfeifer et al. [25] investigated the integration of renewable energy sources and demand response technologies in interconnected energy systems represented with islands to tackle excess electricity generation. They used the energy system simulation tool - EnergyPLAN [26] and MultiNode tool to tackle excess electricity generation. MultiNode tool is an add-on to EnergyPLAN that enables simulation of multiple energy systems and transmission between the systems. Pfeifer et al. [27] also examined the integration of renewable energy, this time with an emphasis on solar power. They found that the interconnection of energy systems and sector coupling reduces critical excess electricity production and thus enables further integration of renewable energy.

This research uses optimization software EPLANopt, developed by Prina et al. [28]. The use of the same software is described in the actual use case by the same authors [29]. In that case, EPLANopt is used to find solutions for an energy system with a high penetration of RES, low emissions, and low cost for the case study on the Italian energy sector. Previously conducted research has already addressed some aspects of the presented problem and formed the solutions that this research expands on. For example, Lund et al. used EPLANopt to examine the performance of low-energy buildings and low-temperature district heating systems [30].

The prominent solution to the energy transition, backed by a large number of mentioned papers, considers the term "sector coupling". For example, Backe et al. [31] investigated sector coupling between heating, transport, and the electricity sector using electric boilers and electric vehicles. In that paper, the curtailment of variable energy sources is avoided with the use of excess electricity in other sectors such as transport or heating. Coupling of electricity generation and the transport sector can be achieved directly with the use of electric mobility or electricity-based energy carriers such as hydrogen or synthetic fuels [32]. Couplings of sectors and implementation of flexibility options are also analyzed by Pavičević et al. [33] with the use of Dispa-SET and JRC-EU-TIMES in the case of five scenarios. The authors of that paper conclude that the transport sector provides the highest opportunity for integration of flexibility options and resulting greenhouse gas emissions reduction. The problems and benefits of V2G integration are examined by Rean et al. [34] with the use of an aggregator to find optimal V2G management strategies in the form of time and power of charging and discharging. Further interaction between electrification of the transport sector, modal shift, and the electricity generation sector is examined by Novosel et al. [35]. The outputs of that paper are modelled curves of interaction between electric vehicles and the electricity grid that can be used on a similar energy system. Mancarella [36] describes the importance of sector coupling to achieve a high-performance renewable energy system. The optimization of a microgrid capacity build-up with the presence of battery storage and electric vehicles and their influence on grid stability is considered by Sadeghi et al. [37]. Haikarainen et al. [38] provide a long-term regional optimization pathway with the inclusion of wind, PV, heat pumps, and thermal energy storage. The case study is performed on the example of a typical Nordic and Mediterranean energy system. The results showed that the coupling between power and heating sectors with the use of electrically driven heating solutions such as heat pumps and electric boilers is a relevant strategy as the result of optimization. The reasoning behind the use of heat pumps and electric boilers is both decarbonization and the ability of flexible operation. Flexible operation is enabled by heat accumulation and thermal storage, which can be optimized with the remaining capacities in mind. Optimization of the storage capacities and their operation has the potential to reduce the volatility of energy prices in the system with a high share of RES. [39]. Also, the cost-benefit analysis for the mentioned decarbonization pathways is performed. Various energy storage methods as well as their operating and economic characteristics are reviewed by Olabi et al. [40]. As stated by the authors, currently the biggest problem with most storage technologies is the uncertainty of market prices in the future and therefore the uncertainty of positive commercial application. Another way of reducing emissions is the employment of carbon capture and storage (CCS) technologies. Achievement of carbon emission reductions with the use of carbon capture and storage technologies is challenging, mainly due to the high energy requirements of the CCS equipment itself. The energy consumed by CCS equipment can range between 15 and 30 % of the total generated electricity. Also, the implementation of the CCS system is more capital intensive on older power plants (Wilberforce et al. [41]). The outlook of carbon capture technologies is discussed and described by Nocito et al. [42] with the main focus being not on storage, but on using captured CO_2 from the highly saturated flue gasses in the generation of synthetic fuels. Bello et al. [43] discuss the use of CO_2 capture in biorefineries and its potential to generate net negative emissions in the transportation sector.

Previously published papers that tackled a similar problem as in this research, focused primarily on the final goals of reaching a given amount of renewable energy or completely decarbonizing some of the sectors. For example, Batas Bjelić et al. [44] considered energy system optimization using similar software, GENopt. GENopt optimizes for maximum integration of renewable energy with a low total annual energy system cost. Plessmann et al. [45] discuss the pathway towards decarbonizing the energy system in South-Eastern Europe. The simulation is carried out based on LCOE, and the model adheres to the emission targets in predefined timeframes. Similarly, the optimization with predefined energy goals is carried out in steps that represent various years in the paper by Kazagic et al. [46]. That paper considers emissions, system costs, as well as the impact on the environment and society, but does not provide an overview of energy system capacities and their impact on CEEP or CF. The greater focus of that paper is on the region-specific problem of emissions from thermal power plants, which vary with capacity factor. Previously mentioned research [24], [29], and [33] use EPLANopt to present only optimal cases at the maximum reachable or some targeted share of RES while also satisfying cost targets as well. The advantage of using optimization software in combination with energy modelling software is the ability to achieve optimal results in a relatively short time. The only required inputs consist of basic energy system data, limitations, and optimization targets. A similar analysis of the economic evaluation of renewable energy system integration was performed by Chung et al. [47]. The authors used inhouse developed software to optimize the Korean energy system and compared the results to those from commercial software like TRNSYS and HOMER. Wang et al. [48] consider capacity planning with economic restrictions on the level of a business park to supply the energy demand of the business park with locally generated energy from renewable sources. Haikarainen et al. [49] discussed the limitations and fallbacks of current energy planning evolutionary methods. It is correctly noted that one of the main weaknesses of most of the models is so-called perfect foresight and that it does not account for the changes and variations in renewable energy generation throughout the year. Also, a notable limitation is often the high computational intensity of such simulations. The mentioned paper also considers only 2-factor optimization, with total annual cost and emissions being optimized. 2-factor optimization is convenient because it enables the authors to display Pareto fronts, but some of the problems remain unsolved. For example, the question of capacity factors of renewable energy generating sources or critical excess electricity generation is often not addressed. Also, constraints may need to be implemented to limit excessive electricity generation from biomass, which may not be sustainable.

Examined technologies and measures

In this research, the examined technologies and measures are displayed in Figure 1. They include capacities of renewable energy sources, the fuel mix in thermal power plants, capacities of flexibility options such as thermal power plant minimum operating power, partloading of nuclear power plants, electrification, and flexibilization of transport with the use of V2G and smart charge, the introduction of P2H, and short to medium-duration energy storage. Also, the refurbishment of buildings is considered, as this measure impacts energy requirements for heating.

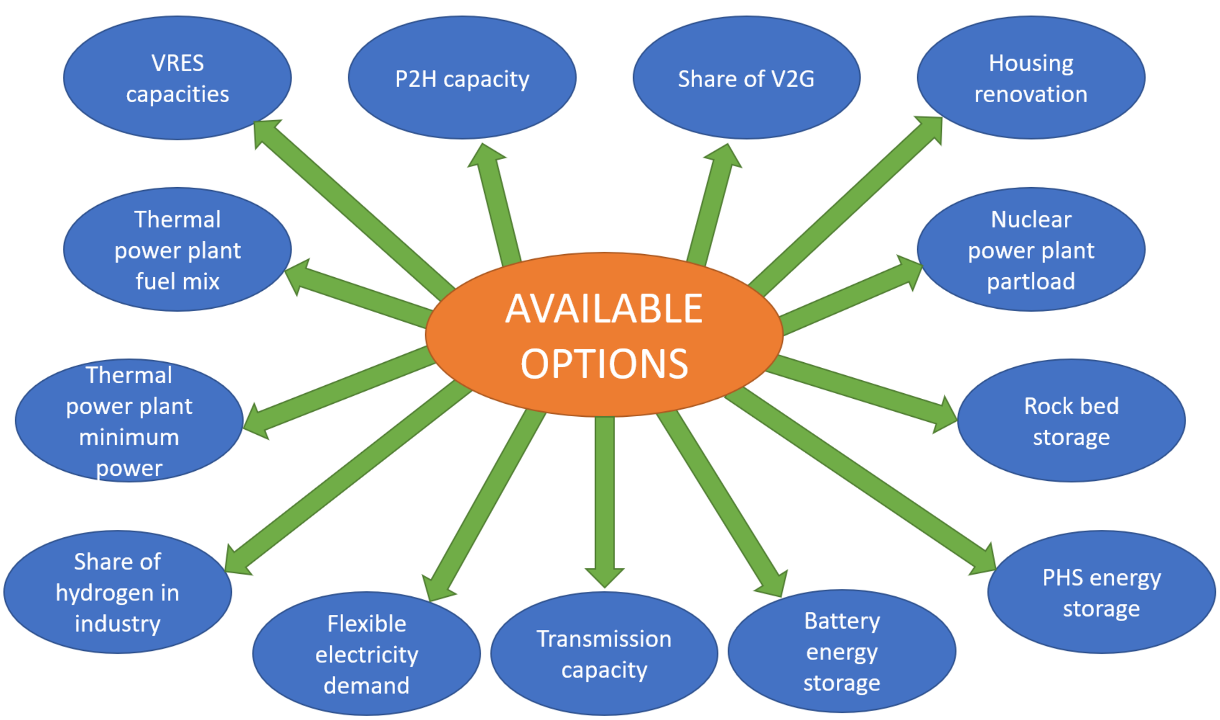


Figure 1. Available options

A more detailed approach to individual flexibility providing technologies in relation to the share of RES for the area in question is presented. Such an approach represents a step forward compared to the reviewed literature. A significant contribution also comes from the method for determining the limit values for investigated flexibility providing technologies as well as avoiding infeasible situations in optimization. This research also uses methods of expert analysis. There are numerous technologies available, each with its own set of features and applications [22], [26], and [34]. The term "expert analysis" refers to the process of determining the limit values of optimization variables used in EPLANopt. The portion of the limiting values of variables considering generating capacities and resources is sourced from the Energy Development Strategy of the Republic of Croatia [4]. The rest of the variable limits are determined following the potential for development and deployment of the examined technology. There is also an emphasis on limiting the available potential in order not to overstate the role of the technology or measure. The other reason for setting limits on the capacity is to comply with the possible development potential of technology. Also, possible interactions between different technologies that may inhibit the possibility of finding an optimal solution had to be accounted for. In that case, a conflict may arise between two ways of achieving the decarbonization of thermal power plants. Synthetic gas can be used in thermal power plants to reduce emissions, but that method won't work and have meaningful effects if the share of natural gas is reduced. Synthetic gas replaces natural gas in EnergyPLAN without the need to modify fuel ratios.

The hypothesis of this research is based on the use of EPLANopt in combination with the methods of expert analysis. The use of the proposed method can determine the optimal path for a gradual energy system transition to a 100 % renewable energy system, even when multiple optimization goals are taken into account.

The contribution of this research in relation to the examined and previously published literature is reflected through:

- Detailed investigation of the influence of various flexibility options in relation to the given percentage of RES and their interaction with other flexibility options or implemented technologies. Interaction and discussion are not limited only to the final solution at a maximum achievable share of RES. This is the main contribution of this research as it manages to provide a complete overview of technology or measure evolution through intermediate stages of reaching a 100 % renewable energy system. The requirements considering emissions, CEEP, total annual cost, and biomass consumption are satisfied, and the optimal solution is determined at each of the intermediate stages.

- This research considers factors other than total annual cost and emissions, which are used by most of the already published papers. This research focuses on critical excess electricity generation and the use of biomass as well. The applied approach does not provide the possibility to display the Pareto front since it optimizes for more than two goals, but it provides more favourable results from the standpoint of energy system management. It tackles the problem of excess electricity generation, which may become a significant problem in the further development of renewable energy systems. Implementation of multiple criteria is accomplished with the use of weight factors, giving different priorities to the optimization goals.

- An investigation of the influence that flexibility options or implemented technologies have on the total annual cost. In the last part of the research, two decarbonization pathways are compared. The main difference between the pathways is a difference in total annual cost, which influences the technologies that are applied. The results of this examination provide information on the applicability of technologies with respect to the reduction of the total annual cost. Published papers offer an insight into optimal energy systems but do not compare different configurations which are the result of total annual cost limits.

Method

The software used in simulations is EnergyPLAN [26] which is used in combination with the EPLANopt [50] optimization algorithm. Figure 2. displays the basic scheme and relations in EnergyPLAN. Data such as energy demand, installed generating capacities, efficiencies, and distributions are required to generate output data. This set of data points is classified as input data. Inputted data values can be divided into two groups for this research. The portion of the values is fixed and have the same values in all of the cases. The remainder of the variables are subject to optimization and their values are determined by EPLANopt. Output data consists of various technical parameters related to generating capacities. In this case, the primarily considered output data is the share of renewable energy in primary energy supply, the critical excess of electricity production, total annual cost, annual CO_2 emissions, and biomass consumption. The critical excess of electricity production (CEEP) is the amount of electricity that would not be generated if the portion of electricity generation from VRES was curtailed.

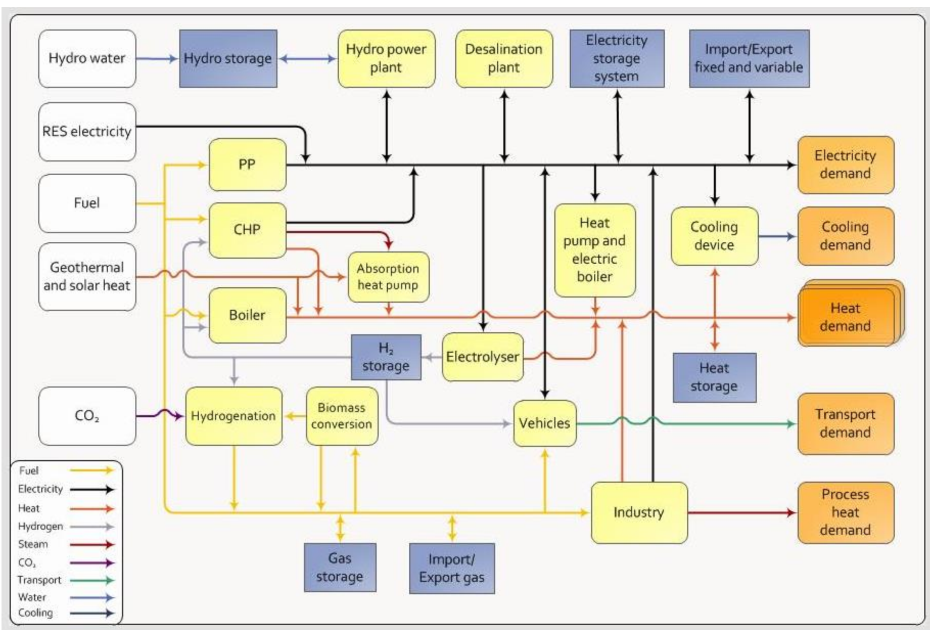


Figure 2. Structure of EnergyPLAN [26]

EPLANopt is an open-source code based on the DEAP genetic algorithm [51] and written in Python. The Spyder Python environment [52] is used to run the algorithm and soft link it with EnergyPLAN.

Simulation and optimization process

The flow chart describing this method of using EnergyPLAN and EPLANopt is presented in Figure 3. The method requires input data consisting of the following parameters, which need to be defined:

- Energy system data and capacities - The energy system has to have defined generation capacities, heat demand, the ratio of the used fuels, and transport electrification.

- Costs of investment and operation - The cases are compared based on total annual cost. Thus, each technology has defined investment and operation costs.

- Variables that are to be optimized - Variables that are to be optimized are defined in the optimization software EPLANopt in such a way that the minimum and maximum values are defined. Optimization software can then choose the value between the defined low and high value.

- Optimization targets - Since EPLANopt is a genetic optimization software, the goals of optimization have to be defined. Optimization targets are defined with weight factors displayed in Table 1. Weight factors are chosen between the values of -1.0 and +1.0. The positive weight factor represents the efforts to maximize the value, and the negative to minimize it.

- The number of generations and size of populations – The algorithm creates a defined number of cases which are then run. This number is called the "population size". Depending on the outcome of each of the cases, the next generation of input parameters is created, which combines the data from several more successful cases in the preceding generation. The problem often faced with this approach is that the algorithm can get “stuck” in a local maximum. To mitigate this, the algorithm restricts the influence of the currently best-performing cases by eliminating some that are positioned close together and do not provide significant diversity to the results that are required to find a global optimum. The used sizes of the population and generation metrics in EPLANopt are both 80. This number is the result of simulations carried out by the authors and provides a balance between accuracy and run time.

The optimization targets defined in EPLANopt are:

- CEEP – minimization – to maintain the system stability and avoid reducing VRES generation sources

- CO_2 – reduction – avoid emissions and achieve climate neutrality

- Total annual cost – minimization – only applies to technologies that benefit final consumers at a low cost while also achieving other objectives.

- Biomass consumption—minimization—avoid relying solely on biomass when achieving 100% RES, putting CO_2 neutrality and sustainability at risk while also increasing particulate matter emissions [19].

- Maximization of RES share
- Minimize electricity imports and avoid relying on external electricity demand regulation. This goal is implemented to limit the role that external energy system regulation has on the stability of an examined energy system. EnergyPLAN assumes the constant availability of cross border transmission capacities which is not entirely accurate.

Table 1. Optimization weight factors

Variable	Weight factor
CEEP	- 1.0
CO_2	-1.0
Total annual cost	-1.0
Biomass consumption	-0.5
RES share	+1.0
Electricity import	-0.5

Due to certain limitations of the used version of EPLANopt, some of the inputs have to be predefined manually. Only independent variables can be defined as input variables in EPLANopt without causing inconsistency problems. Independent variables are the ones that are able of completely defining the technology without the necessity of also changing the value of another variable in some relation to the first variable. For example, if a variable "Smart charge" is defined as an optimization variable, EPLANopt would optimize its value without compensating for the values of other sources of energy in the transport sector. Therefore, the "Smart charge" variable is not independent. The values that are used for the definition of dependent variables are displayed in Table 2.

Implementation of V2G and smart charge technology is considered in the range between 0 and 100 %. The remaining transport is provided with a combination of biofuels and synthetic fuels as an alternative to full electrification while also being able to be applied at 100 % of the RES system. Electricity demand is considered flexible up to 50 % of total demand. Residential demand is flexible on a daily (24-hour) basis, commercial demand is flexible on a weekly basis, while industrial demand is flexible on a monthly basis. The timespan of demand flexibility indicates in which time ranges certain loads can be shifted.

The data by which the simulation runs differ is stated in Table 6.

Table 2. Used values for dependent variables

V2G and smart charge	Demand flexibility	Energy efficiency improvements
%	%	%
0	0	0
50	25	50
100	50	100

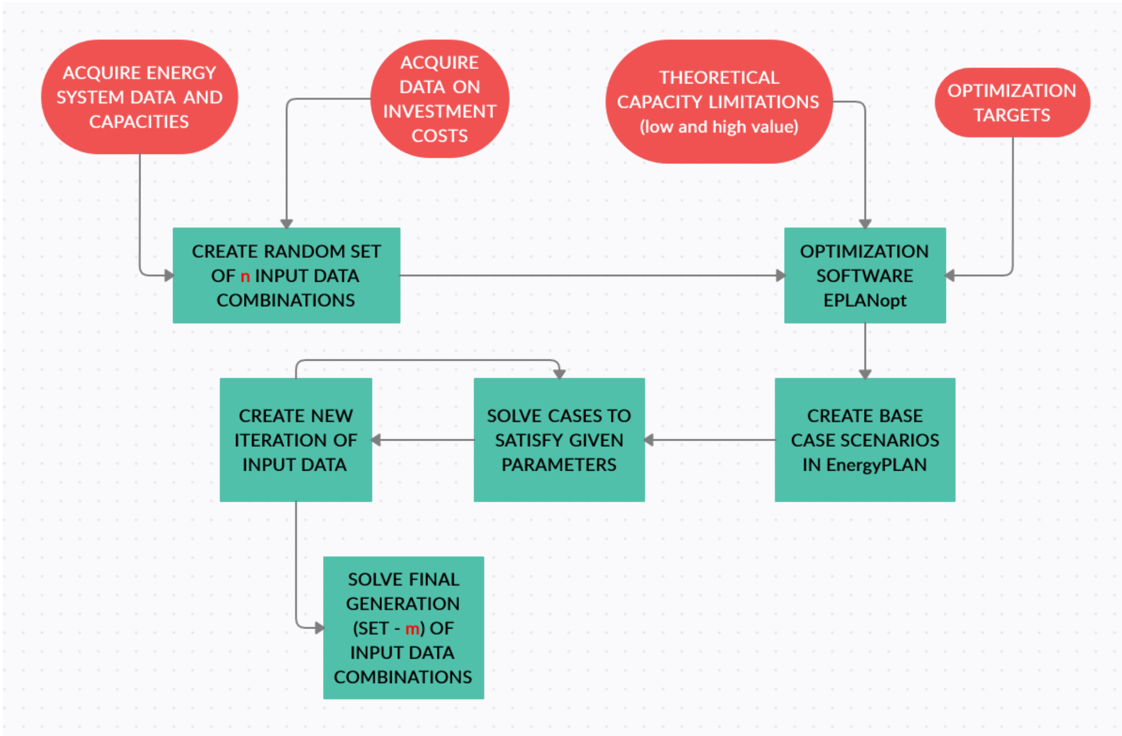


Figure 3. Flow chart of the process in EPLANopt and EnergyPLAN [53]

Post-processing of output data

Figure 4. describes a post-processing procedure that enables a determination of favourable pathways towards decarbonization which also includes all intermediate stages. The second post-processing pathway offers a preview of the technologies used in lower or higher cost pathways. The input for this part of the process are outputs from the process in EnergyPLAN and EPLANopt described in Figure 3.

Total results from the genetic algorithm are divided into 12 segments on which the further processing is done. After this step, the process divides into two pathways where one displays the progression of optimal solutions towards a high share of renewables, low CO_2 emissions, CEEP, cost, and biomass use. The second part displays differences in approaching a high share of RES and low CEEP in relation to the total annual cost.

- Optimal decarbonization pathway:
  Each of the solution segments is studied individually. Since optimization software is used, the more frequent values chosen by the software are optimal.
  The value displayed in charts is the average value of cases in a given segment.
- Comparison of optimal and sub-optimal pathways:
  Results are divided according to the total annual cost group they fall into. 2 extremes are chosen, one with the total annual cost between 8.5 and 9 B€, while the other considers the results between 11.5 and 12 B€. The same procedure of acquiring average values is carried out. The results are compared.

The following part of the text and Figure 4. detailly explain the procedure.

1. Results are divided into 12 segments indicated by the share of RES. Each segment is 2.5 % RES wide and segments range from 70 to 100 % of RES. After this step, the process divides into two pathways.
   1.1. In the first pathway, an average value is determined for each of the variables in the data set.
      1.1.1. The data presenting the results is combined and put into the new table
      1.1.2. The charts are created for each of the technologies used
      1.1.3. The results are discussed
   1.2. In the second pathway, results are grouped according to the total annual cost.
      1.2.1. Two total annual cost ranges are defined where one describes the range of values with lower total annual cost, while the other describes values with higher total annual cost.
      1.2.2. The charts are created for each of the technologies used
      1.2.3. The results are discussed

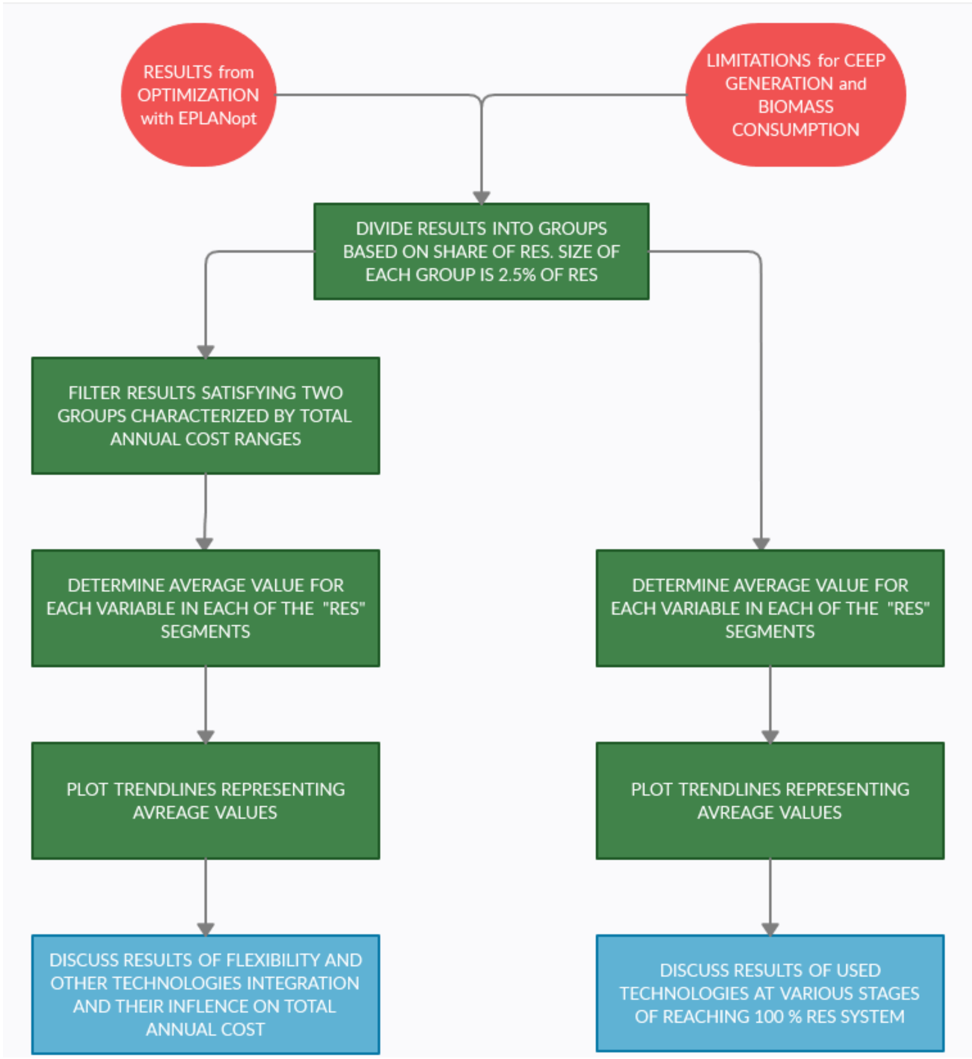


Figure 4. Flow chart of the post-processing procedure

After the post-processing process described in Figure 4. is performed, the final task is to discuss the results. Results are discussed based on relations between the share of RES and utilization of considered technology, which is in turn applied to each share of RES accordingly to its ability to limit the generation of a critical excess of electricity, reduce total annual cost, as well as CO_2 emissions and use of biomass. The same procedure applies to the results of the economic comparison of an affordable and more expensive pathway towards total system decarbonization.

Case study

The implementation of the EnergyPLAN and EPLANopt has been done on the case of the Croatian energy system. The base model of the system is the EnergyPLAN model, which describes the Croatian energy system in the year 2030, with assumptions of an average hydrological year [54].

The model is calibrated based on the year 2018. Calibration data is sourced from the IEA, IRENA, and Eurostat. Table 3. displays used calibration data and model output data. The error in relation to the real-world data is sufficiently small.

Table 3. Model calibration data

Value	Unit	EnergyPLAN value	Reference source value for 2018	Relative error	Source database
Share of renewable energy in final energy consumption	%	28.7	28	+ 2.5 %	Eurostat [55]
CO_2 emissions	Mt	15.7	15.3	+ 2.6 %	IEA [56]
Wind power capacity factor	%	25.97	25.93	+ 0.1 %	IRENA [57]
PV capacity factor	%	12.60	12.59	+ 0.1 %	IRENA [57]

Assumed constant values in each of the cases are presented in Table 4. And the overview of the Croatian energy system is presented in the papers by Cerovac et al. [11] and Pfeifer et al. [26].

Table 4. Data on the Croatian energy system in 2030. – reference case

Name	**Value**	**Unit**
Cogeneration power plant capacity	830	MW
Cogeneration power plant capacity in back-pressure operation	620	MW
Dammed hydropower plant capacity	1707	MW
River hydropower capacity	521	MW
Geothermal power plant capacity	100	MW
Total electricity demand	18	TWh
Total heat demand	19.9	TWh
Use of biomass for heating	7.6	TWh
Use of heat pumps for heating	10	TWh
COP for heat pumps	4	-
Use of district heating	2.5	TWh

Most of the costs data used are derived from the EnergyPLAN cost database [58], while the rest, which is not included in that database, is shown in Table 5. The fuel price projections are taken from the Heat Roadmap Europe project [59].

Table 5. Investment price corrections [60], [61], [62]

Technology	**Cost**	**Unit**
Electric vehicles	25000	€/vehicle
Conventional vehicles	31000	€/vehicle
Power plant flexibilization	6	M€/100MWflex
Demand flexibilization	200	€/household
Demand flexibilization	1000	€/Industrial consumer
Industry electrification	0.1	M€/MW

Table 6. List of predefined variables in separate runs

	Transport V2G and smart charge	**Demand flexibility**	**Energy efficiency improvements from 2030 to the 2050 projection**	**Industry electrification**
Run number	**%**	**%**	**%**	**TWh**
1	100	0	0	10
2	100	0	50	6
3	100	0	100	4
4	100	50	0	10
5	100	50	50	6
6	100	50	100	4
7	100	25	0	10
8	100	25	50	6
9	100	25	100	4
10	50	0	0	10
11	50	0	50	6
12	50	0	100	4
13	50	50	0	10
14	50	50	50	6
15	50	50	100	4
16	50	25	0	10
17	50	25	50	6
18	50	25	100	4
19	0	0	0	10
20	0	0	50	6
21	0	0	100	4
22	0	50	0	10
23	0	50	50	6
24	0	50	100	4

25	0	25	0	10
26	0	25	50	6
27	0	25	100	4

The variables which are subject to optimization are listed in Table 7. These variables include:

- Wind capacity
- PV capacity
- Fuel mix in thermal power plants
- Battery storage capacity
- Pumped hydro capacity
- High-temperature thermal storage
- P2H capacity
- Thermal power plant minimum operating power
- Nuclear power plant part load
- Transmission capacity

Other optimized technologies and options are described in Table 6. Are:

- Vehicle to grid (V2G) and smart charge
- Demand flexibility
- Implementation of energy efficiency improvements
- Industry electrification

The next step is to determine upper values that can be inserted into the model:

- Capacities of VRES generators - Possible VRES expansion capacities are taken from the Energy Strategy of the Republic of Croatia [4].
- Thermal power plant minimum operating power – determined following the provided data by HEP utility company, an operator of thermal power plants in Croatia [63].
- Capacities of thermal energy storage in district heating and P2H capacity - The system uses the combination of heat pumps and electric heaters to provide connection of electrical and heating system. An average energy conversion factor is estimated to be 2.5. The capacity of used thermal storage and heat pump capacity is modelled following an actual heating load. With maximum capacity, the system can store up to 48 hours of average heating season district heating load, while the storage can be filled up during 4 hours of excess electricity thought this time may vary due to the ever-changing amount of excess electricity being available.
- Pumped hydro storage – an increase in capacity and storage capacity achieved by retrofitting existing dammed hydropower plants to operate in pumping mode. The capacity of 60 GWh corresponds to the storage of 20 hours of average electricity demand.
- Battery storage - a storage capacity of 200 GWh is equivalent to storing 60 hours of average electricity demand.
- High-temperature rock bed thermal storage - Storage capacity of 100 GWh corresponds to the storage of 30 hours of average electricity demand.

Table 7. List of variables [4], [54]

Variable	**Lower value**	**Higher value**	**Unit**
Wind capacity	1300	9000	MW
PV capacity	2000	8000	MW
Power plant minimum operating power	0	400	MW
Transmission capacity	3000	10000	MW
P2H capacity	100	2000	MW
DH storage capacity	0	20	GWh
Coal in power plants	0	0	Relative variable
Natural gas in power plants	0	1	Relative variable
Biomass in power plants	0	1	Relative variable
Natural gas in CHP	0	1	Relative variable
Biomass in CHP	0	1	Relative variable
Natural gas in DHP	0	1	Relative variable
Biomass in DHP	0	1	Relative variable
PHS pump capacity	257	1000	MW
PHS turbine capacity	293	1000	MW
PHS storage capacity	3	60	GWh
Battery storage charge capacity	0	50000	MW
Battery storage discharge capacity	0	50000	MW
Battery storage capacity	0	200	GWh
Rock storage charge capacity	0	50000	MW
Rock storage discharge capacity	0	50000	MW
Rock storage capacity	0	100	GWh

Previous work addressing the problem of Croatian energy system optimization has been performed by Prebeg et al. [64] on the case of electric vehicle integration, while Herc [65] performed brute force analysis of possible pathways. The difference to the paper from Prebeg et al. [63] is that he studies electric vehicles and their relation to the grid, while this research tries to envelop the whole energy system. Similarly, although a different method is used, this research contains most of the same limitations in the capacity as the thesis by Herc [65]. The main difference is the implementation of dependent variables, which in this research are inserted and optimized individually. On the other hand, the variables in the cited thesis are tied in clusters that enable the linkages between variables associated with the same technology in EnergyPLAN. Also, Pfeifer et al. [26] studied the integration of flexibility options and their impact on system stability and provided the relations that are used in this paper.

Results

The results of the optimization are shown in Figure 5. It can be observed in Figure 5a. that a higher RES share may not necessarily lead to a higher CEEP as there is a large number of results that satisfy the necessity for CEEP <=5 %. Also, out of 14604 cases that satisfy grid stability and biomass consumption parameters from Table 8, 91 % of cases managed to achieve CEEP < 1 %.

The results of optimization show a reduction in total annual cost in relation to the penetration of renewables displayed in Figure 5b. The total annual cost is in the range between 8 B€ and 13 B€, with a majority of cases with higher penetration of RES having lower values as indicated by the trendline. CO_2 emissions also decrease with the increase of renewables, and there is potential to reach 0 Mt of CO_2 emissions. (Figure 5c.). On the other hand, average biomass consumption increases as shown in Figure 5d, but it is also observable that it is possible to have low biomass consumption, as shown in Figure 14. The limit on biomass use is set to a sustainable level of 40 TWh, following the technical potential in the Energy Development Strategy of the Republic of Croatia until 2030 with an outlook to 2050 [4].

Table 8. Output requirements

Parameter	Value	Unit
CEEP	< 5	%
Biomass consumption	< 40	TWh

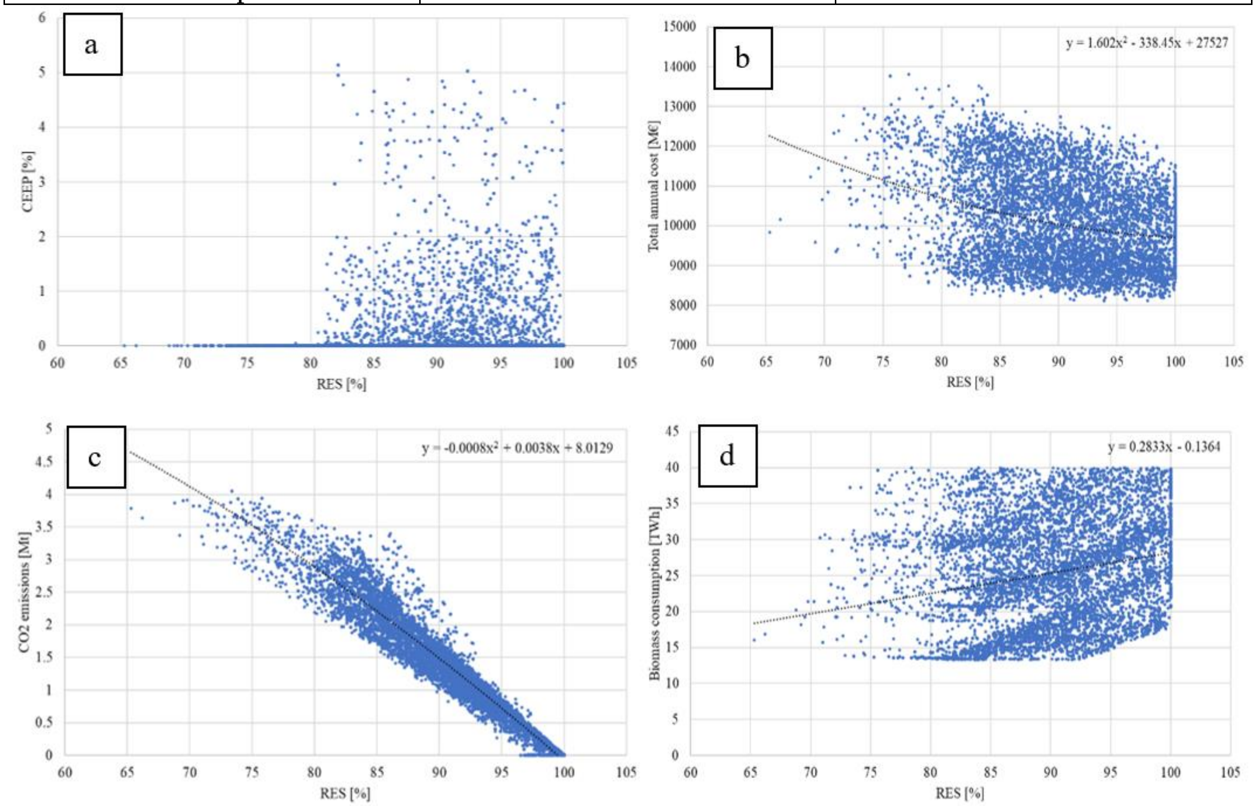


Figure 5. Relation of RES and CEEP (a), Relation of RES and Total annual cost (b), Relation of RES and CO_2 emissions (c), Relation of RES and biomass consumption (d)

The following charts display optimal values for each of the technologies used in the simulations. Each dot represents the average value of the technology capacity used in each of the 2.5 % of RES wide segments.

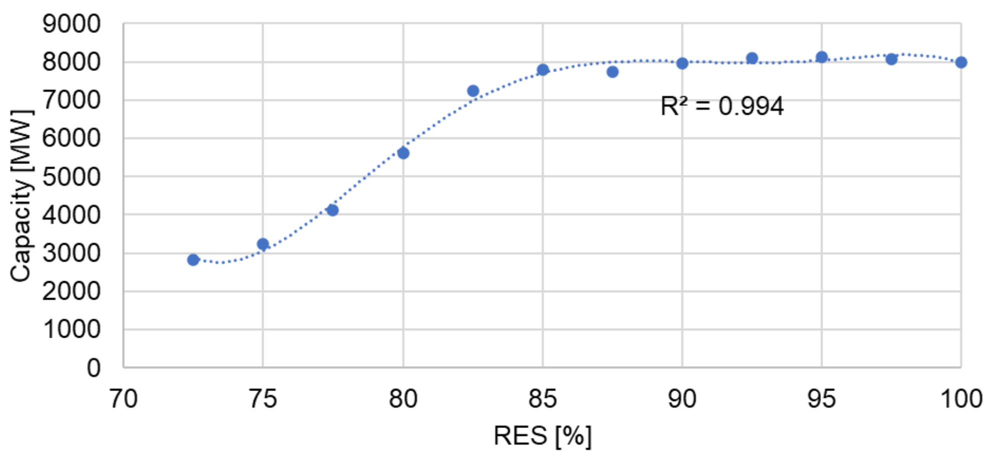


Figure 6. Results for optimal wind power capacity

As shown in Figure 6, optimal wind power capacity is 3000 MW at a lower penetration of renewables, while it rapidly increases and stagnates at the capacity of 8000 MW from 80 % of RES up to 100 %, as shown in Figure 5. Wind power potential from the Croatian energy strategy is 9000 MW [4], so almost 90 % of the potential is required to be installed.

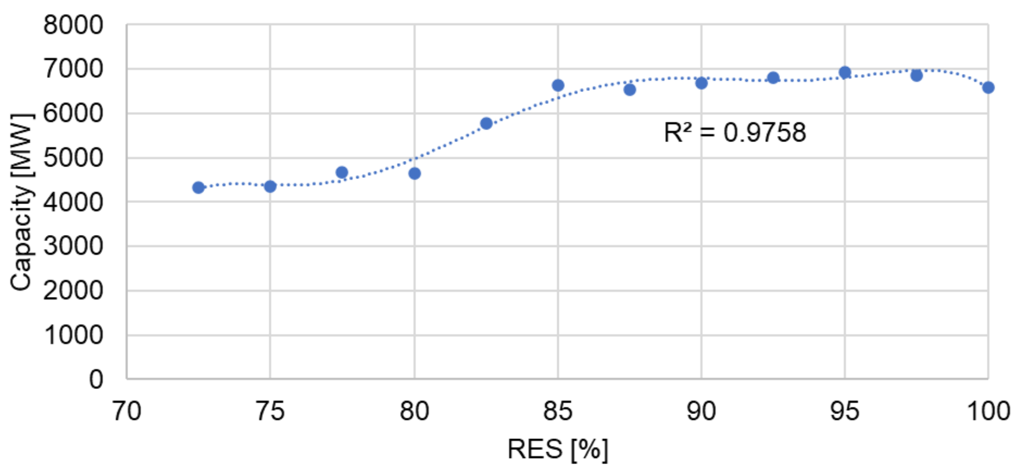
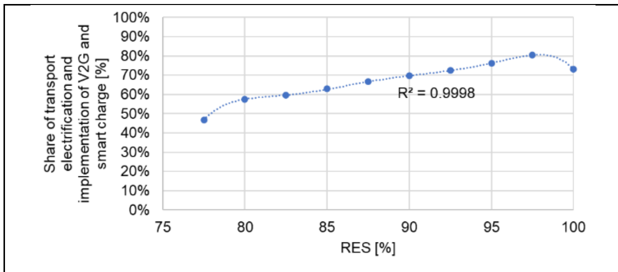


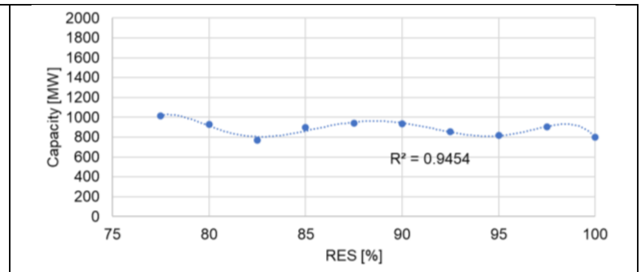
Figure 7. Results for optimal PV

The results for PV integration are displayed in Figure 7. The optimal PV power capacity in Croatia is 4000 MW at a lower penetration of renewables and it continually increases up to a capacity of 7000 MW, which is optimal capacity in the range of RES from 85 up to 100 %. Similarly, as for wind power, the stated PV potential is 8000 MW [4], so almost full capacity is being used. This means that for the system with 100 % RES, the optimal combined capacity of wind power and PV is 15000 MW. Wind capacity expansion is preferred over PV capacity expansion, particularly at lower RES share levels of 70 to 80 %. The reason behind this behaviour is because wind power has a higher capacity factor and lower variations in generation than PV, making it easier to integrate into the system.

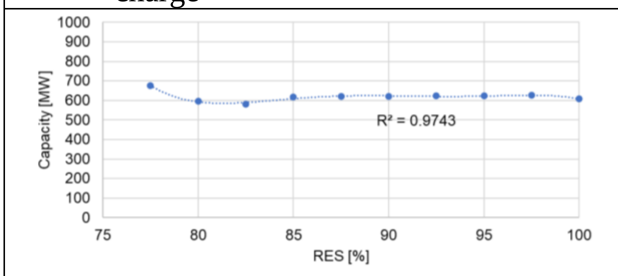
The results for the introduction of flexibility options and energy system management options are displayed in Figure 8.



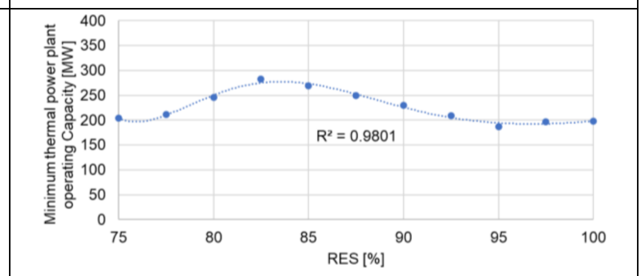
A. Results for optimal V2G and smart charge



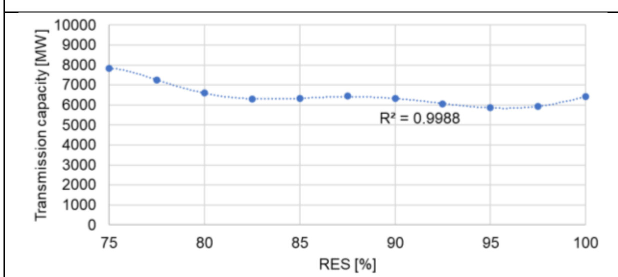
B. Results for optimal P2H capacity



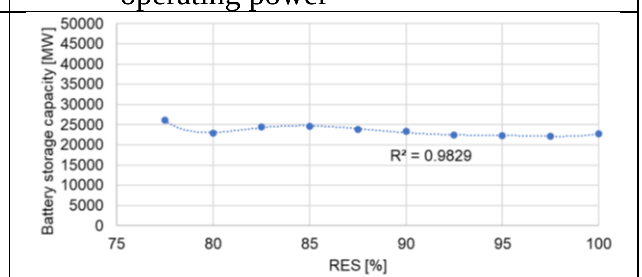
C. PHS Pump capacity



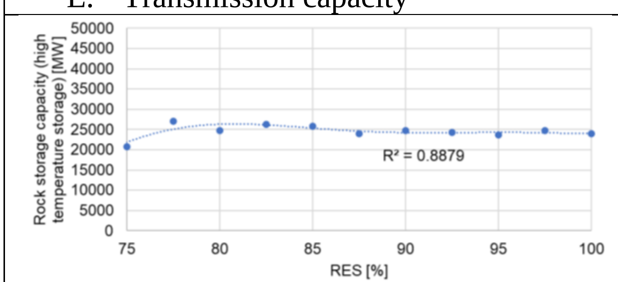
D. Thermal power plant minimum operating power



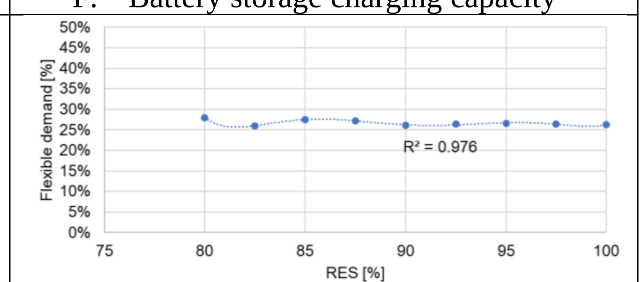
E. Transmission capacity



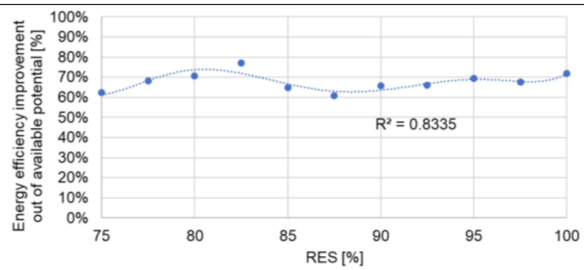
F. Battery storage charging capacity



G. Rock storage



H. Flexible demand



I. Efficiency improvements

Figure 8. Results

The optimal capacity of V2G and Smart Charge is 50 % with a lower share of renewables, increasing to 75 % with 100 % renewables share. It should be noted here that the rest of transport, which is not included in V2G and the smart charge, is powered by the combination of synthetic fuels and biofuels to be able to reach 100 % of RES even without complete transport electrification. Implementation of transport electrification is highly affected by the share of RES. The reason for such an increase in electrification for a system with a 100 % RES energy supply is in part due to the ability of V2G to provide the role of energy storage, which is something that the use of synthetic fuels and biomass lacks. Also, direct electrification is more energy-efficient and thus requires smaller generating capacities.

As the share of V2G increases, there is no significant leftover demand for additional balancing capacities due to the scale of balancing that V2G offers. Also, the capacity of P2H does not increase since it is integrated into a district heating system whose energy demand does not increase. Capacity decreases from more than 1000 MW at 75 % of RES to a constant capacity of 900 MW from 80 % of RES till 100 % which is shown in Figure 8B.

The optimal capacity of pumped hydro energy storage is 650 MW and it does not change significantly over the whole range of RES from 75 to 100 %. The results are displayed in Figure 8C.

Thermal power plant minimum operating capacity is between 200 and 300 MW for the whole range with capacity at higher RES share being 200 MW. The explanation of low optimal capacity at 75 % of RES is due to lower utilization of other flexibility options at this range such as V2G and rock storage. The results for the thermal power plant minimum operating power are displayed in Figure 8D.

Transmission capacity's optimal capacity is in the range between 6000 and 8000 MW. Optimal capacity is lower at a higher share of RES due to one of the optimization targets aiming to reduce electricity import payments and import itself. The reasoning behind this is to reduce dependency on the region for balancing the grid. Also, additional reasoning is to eliminate problems with an insufficient domestic generation that can come up with the combination of relatively restricted VRES potential as in this case and electrification of a large amount of industry, transport, and heating. The results are shown in Figure 8E.

The optimal battery storage charging capacity is shown in Figure 8F. is around 25000 MW for the whole RES range. The results for rock storage optimal capacity in Croatia are displayed in Figure

8G Optimal capacity is in the range of 25000 MW for most of the RES range, while at a lower share of RES it is around 20000 MW.

The optimal capacity of flexible electricity demand is the same for the whole RES range, which is between 25 and 30 % of the basic electricity demand. The results are displayed in Figure 8H.

Efficiency improvements are also used with the optimal amount being 70 % of the proposed improvements described in the document describing the modelling of energy requirements of the Croatian energy system by 2050 in RESFLEX project [66]. The results are shown in Figure 8I.

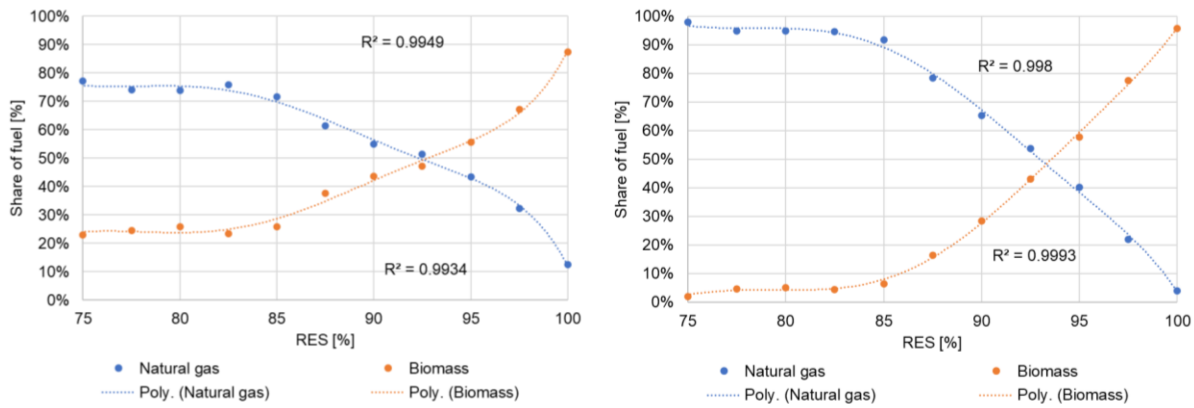


Figure 9. Share of natural gas and biomass in cogeneration (left) and condensing (right) plants

The fuel mixes in cogeneration and condensing plants are displayed in Figure 9. In both cases, natural gas is completely replaced by biomass at 100 % of RES which is also expected as the goal of optimization is to reach a 100 % RES system.

The transition towards a completely renewable energy system requires the increase of VRES installed capacities. Fulfilment of such goals is accomplished in combination with other measures. These include the increase in the thermal energy efficiency of buildings, energy storage technologies, as well as the introduction of V2G.

The following figures display the results for two separate pathways. Cheaper pathway represented by the cases with a total annual cost between 8.5 and 9 B€ and the more expensive pathway represented by cases with a total annual cost between 11.5 till 12 B€ are examined to determine the main differences in used technologies in these two different groups of cases.

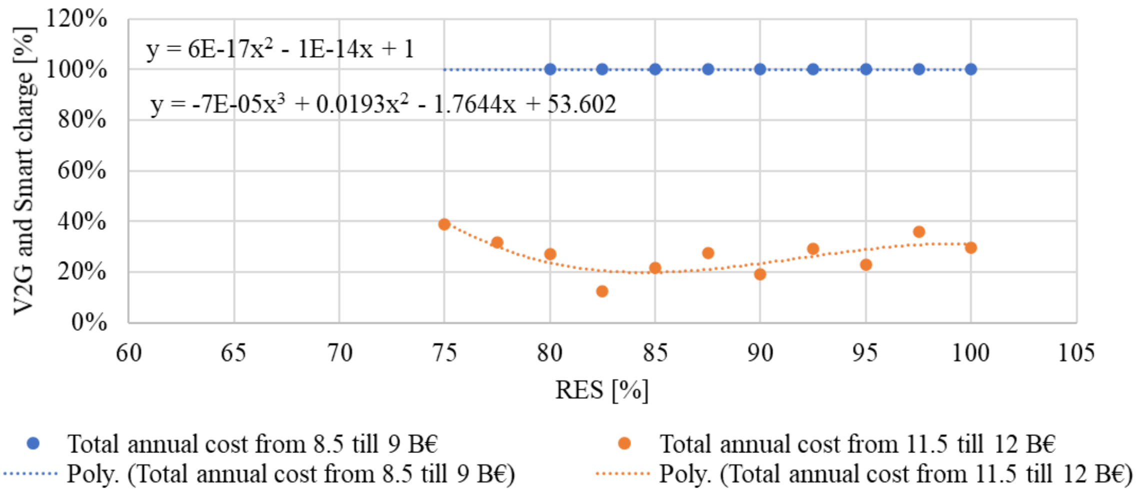


Figure 10. Comparison of V2G and smart charge use for cheaper and more expensive pathway

The comparison of V2G and smart charge used in cheaper and more expensive pathways is displayed in Figure 10. V2G and smart charge utilization is 100 % for the entire examined RES range in a cheaper scenario, whereas more expensive pathways use 30 % of V2G and smart charge potential on average. The use of V2G has been shown to be effective in the reduction of costs when compared to the alternative. In the case of the transport sector, an alternative is the use of hydrogen and biomass, both of which are considered more expensive than electrification, both in terms of investment and in terms of their influence on the rest of the energy system.

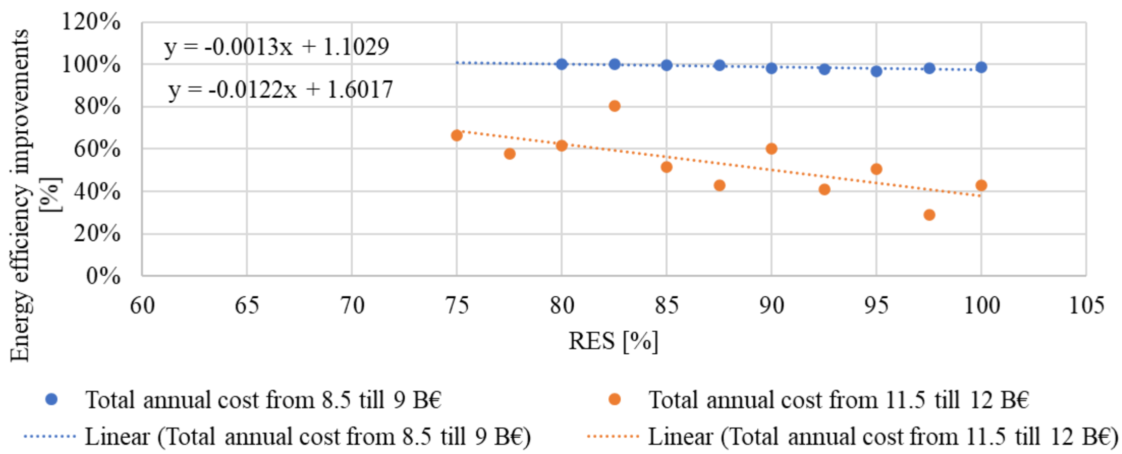


Figure 11. Comparison of energy efficiency improvements in a cheaper and more expensive pathway

The comparison of efficiency improvements in a cheaper and more expensive pathway is displayed in Figure 11. Improvements in the cheaper pathway are fully implemented for the whole RES range, while optimal improvements in the more expensive pathway range from 70 % at the lower RES share and decrease to 40 % at 100 % of RES. The decrease in a more expensive pathway is due to the increase in costs from synthetic fuel integration, and thus energy efficiency is not being fully implemented.

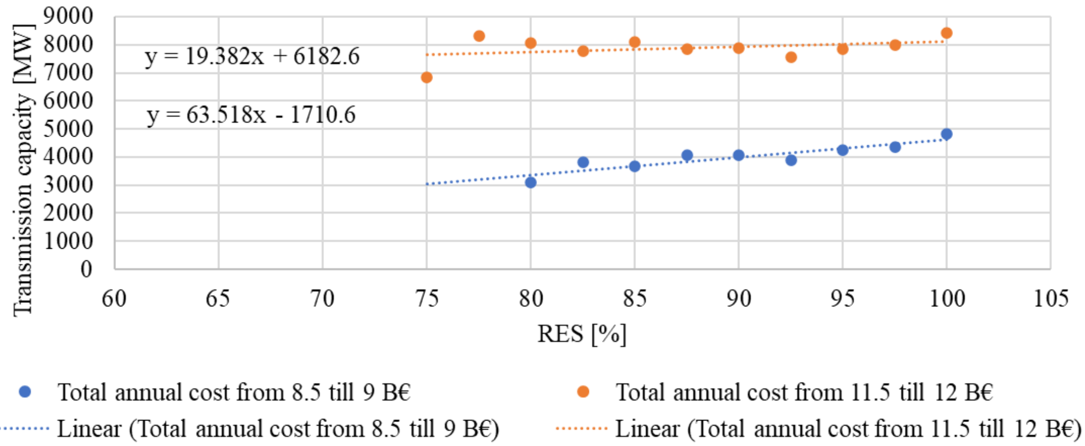


Figure 12. Comparison of transmission capacity in a cheaper and more expensive pathway

The optimal transmission capacity for cases with the higher total annual cost is between 7000 and 9000 MW, while for the cheaper pathway, it is in the range from 3000 MW at 80 % of RES up till 5000 MW at 100 % RES. This figure shows that investment in transmission capacity can be avoided, which has the additional benefit of not relying on the cross-border energy market for system stabilization. It is interesting to note that greater interconnectivity with neighbouring energy systems is deemed unaffordable due to higher estimated electricity prices used in the external market than the model has determined for inside the system. The comparison of transmission capacity in the cheaper and more expensive pathways is displayed in Figure 12.

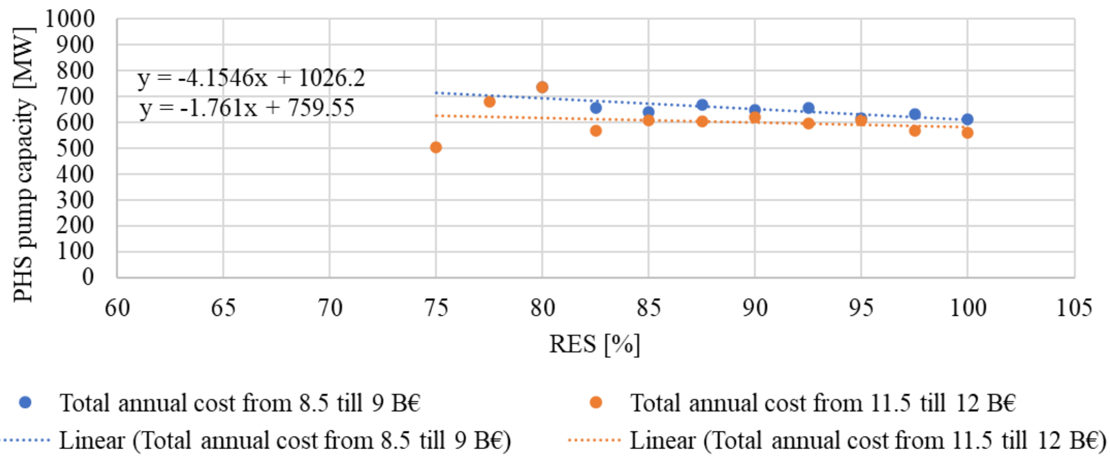


Figure 13. Comparison of PHS pump capacity in the cheaper and more expensive pathway

The differences in PHS applicability for the cheaper and more expensive pathways are displayed in Figure 13. It can be noted that the cheaper pathway offers approximately 50 MW larger capacity for pumped hydro storage, especially for the lower range of RES, while the difference decreases at 100 % of RES and accounts for 600 MW for both cases.

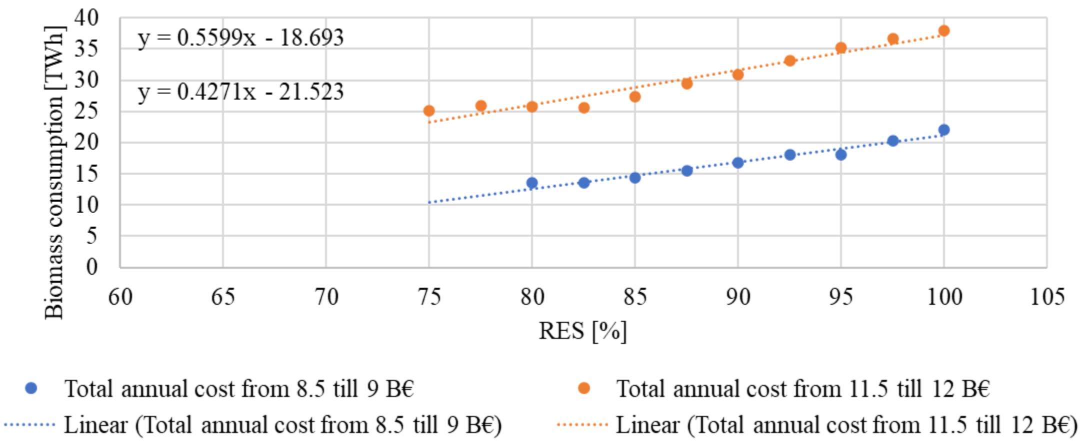


Figure 14. Comparison of biomass consumption in the cheaper and more expensive pathway

The results for biomass consumption in two of the economically different scenarios are displayed in Figure 14. It can be observed that the less expensive scenario uses less of the biomass, with a maximum consumption of 22 TWh, while the more expensive pathway consumes up to 38 TWh.

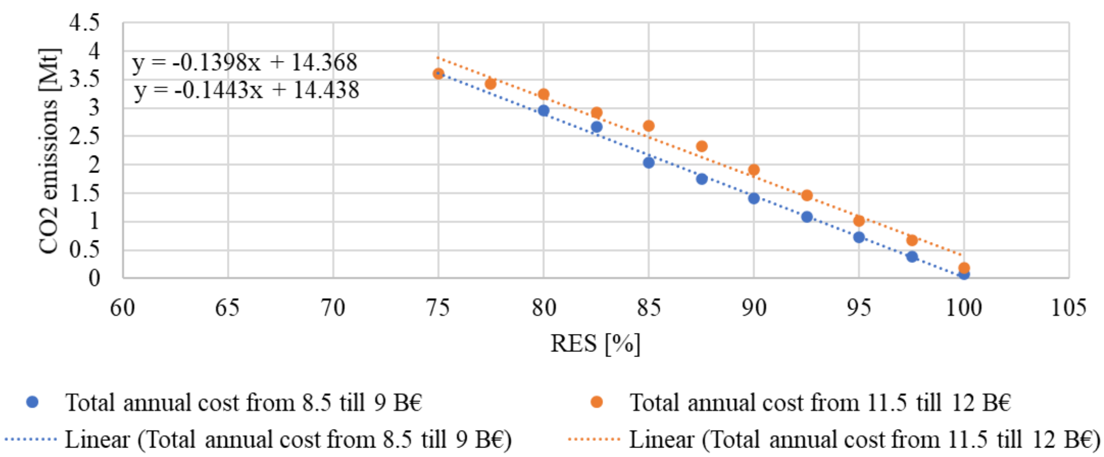


Figure 15. Comparison of CO_2 emissions in the cheaper and more expensive pathway

The pathway with the lower annual cost also has lower CO_2 emissions for the whole RES range, which is approximately 0.5 Mt lower than for the more expensive pathway. The results are displayed in Figure 15.

Significant differences in capacities are present as a function of different total annual cost limits. Various pathways towards energy system decarbonization are available, but they can vastly differ in total annual costs based on which technologies and their combinations are utilized.

In comparison to already published papers that use EPLANopt, such as [29] and [30], the presented research offers a more extensive and comprehensive look into the various aspects of an energy system. This research looks at the energy system as a whole and optimizes multiple aspects of the system. These include the share of renewable energy, critical excess electricity production, CO_2 emissions, total annual cost, biomass consumption, and imports of electricity. Previous research has concentrated on obtaining Pareto curves for a two-variable problem. These are, most commonly, total system cost and renewable energy share. Also, the results are examined at multiple points between the share of renewable energy of 70 and 100 %. Another novel feature is the differentiation of various energy transition pathways based on total annual cost constraints. Expert analysis is a significant factor in obtaining the results.

Conclusion

The method of combining EnergyPLAN with EPLANopt and applying post-processing with consideration of differences in the application of technologies through a range of RES from 70 % up to 100 % has provided results on optimal technology application at a wide range of RES values. The presented method has taken into account multiple optimization goals ranging from energy generation mix, emissions, system cost, use of resources, and imports of electricity. This method has also provided information on the main differences in flexibility integration as a function of the total annual cost. The "expert analysis", most notably in the realm of selecting the variables, has also proved useful in obtaining desired results.

The results show that the most widely implemented technologies in optimal solutions, other than VRES installation, are V2G and Smart charge, as indicated by Figure 7. and Figure 10. The implementation of V2G and smart charge reaches a high share of implementation of above 70 % for the share of RES above 90 % as shown in Figure 7. If strictly accounted for total annual costs as presented in Figure 10, 100 % of the results show the necessity for a complete transition of the transport sector towards transport electrification with the use of V2G and Smart charge for the whole examined RES range. The second notable measure is the application of energy efficiency improvements in consideration of heating systems, as shown in Figure 15. The optimal share of energy efficiency improvements varies but is constantly above 60 %, indicating the significant impact that this measure has on the fulfilment of energy transition goals. Therefore, the method is deemed to be able to provide the modellers with a useful overview of investment into capacities, flexibility options, or implementation of measures.

In the case of the scenario with a total annual cost of between 11.5 and 12 B€, electrification of the transport sector remains at 30 %, while for the lowest cost system, with a total annual cost between 8.5 and 9 B€, the transport sector is fully electrified. It can be concluded that the use of some technologies such as V2G and smart charge, energy efficiency improvements, and PHS has a positive correlation with the total annual cost reduction. On the other hand, for transmission capacity, there is a negative correlation. An additional benefit of choosing a more affordable pathway is on average 15 TWh lower biomass consumption as stated in Figure 15.

Taking into account expected increases in energy efficiency and demographic trends, Croatian base electricity demand with the exclusion of electric mobility, heat pumps, and electric heaters, does not increase significantly over the 2018 level. It is possible to achieve a 100 % renewable energy system by combining increased VRES installed capacity, flexibility options, demand response technologies, efficiency improvements, and the phase-out of fossil fuels.

Further work on this topic requires a more detailed investigation of technologies not included here, like synthetic fuels, hydrogen, and the ratios of fuels in households. Also, improvements in optimization software are being developed to remove restrictions on the use of dependent variables in EnergyPLAN, like inputs in the transport sector which are modelled manually for this research. Additional improvement is the ability of software to target a predetermined share of renewable energy or level of emissions which provides more detail and faster convergence in comparison to the presented method. Another notable improvement deals with the implementation of variable restrictions on the capacities as a function of year or share of RES. This improvement will enable the introduction of gradual capacity build-up and offer different results for different years which has often not been the case in the results presented in this research. With these improvements in place, more detailed optimizations may be carried out at less of an expense of time.

The case study is carried out on the example of the Croatian energy system, but there are no limitations in the application of the same method to other energy systems.

Acknowledgement

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