Multi-objective long-term optimization of energy systems with high share of renewable energy resources

Conference Paper · July 2014

4 authors:

Goran Gasparovic
15 PUBLICATIONS **35** CITATIONS
SEE PROFILE


Pero Prebeg
University of Zagreb
15 PUBLICATIONS **35** CITATIONS
SEE PROFILE


Goran Krajacic
University of Zagreb
67 PUBLICATIONS **459** CITATIONS
SEE PROFILE


Neven Duic
University of Zagreb
407 PUBLICATIONS **1,609** CITATIONS
SEE PROFILE

Multi-objective long-term optimization of energy systems with high share of renewable energy resources

G. Gašparović[a]
[a] Power Engineering and Energy Management Chair
Department of Energy, Power Engineering and Environment
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia
e–mail: goran.gasparovic@fsb.hr

P. Prebeg[b], G. Krajačić[a], N. Duić[a]
[b] Construction of Naval Vessels Chair
Department of Naval Architecture and Naval Technology
Faculty of Mechanical Engineering and Naval Architecture
University of Zagreb, Zagreb, Croatia

ABSTRACT

The paper presents the results of the ongoing research with a goal of investigating the possibility of improvement of the planning of the supply side of energy system with high share of Renewable Energy Sources (RES). The problem consists in selecting appropriate generating and storage components and their sizing for a scenario in a horizon of twenty years, with linear increase of demand side of energy system. Due to stochastic nature of RES, it is necessary to integrate expensive storage capacities into an energy system with high share of RES.

Two-level approach is used in this study. On the global level multi-objective optimization is generating Pareto frontier with the objectives of minimizing overall Net Present Value of energy system (NPV), minimization of NPV levelized by produced energy and minimization of RES capacities. Design variables on this level are starting nominal installed power of power plants and yearly increase of nominal power of each power source.

On the local level, coverage of the demand for each hour is assured. Local level in a current study is divided in 24-hour segments in which regulation of non-RES power plants and electric vehicle (EV) storage secures availability of electricity to satisfy the demand side of the energy system. Two approaches are under investigation on the local level. In the first, regulation is done using expert knowledge, while in the other optimization is applied to a problem that encompasses 24-hour segment with objective of minimization of operating costs.

This approach was applied to a case-study of Dubrovnik with the integration of EV serving as battery storage in Vehicle-to-Grid (V2G) mode. The preliminary results suggest that it is possible to decrease the amount of installed capacity for the scenario that applies optimization on the local level and decrease the initial investment costs, due to better control of the charging and discharging cycles of EV storages.

Keywords:
Optimization, storage, V2G, EV, NPV, RES

INTRODUCTION

In order to satisfy European Union (EU) regulations in reducing the carbon footprint and achieve energy consumption reductions with increase in efficiency, the transport sector provides an ideal environment to implement some of the goals. EU Directive 2009/28/EC specifies minimum of 10% share of RES in the transport sector by 2020 **[1]**. To satisfy these requirements, an increased electrification of personal transportation for short distances is inevitable. Croatia's National Energy Action Plan for RES up to 2020 **[2]** defines a share of 1.9% in 2016 and 9.6% RES in 2020 for purposes of road transportation. The financial aspects is already being implemented in form of subsidies for purchase of Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV) and Battery Electric Vehicles (BEV), and encompassing other types with an equivalent emission standard of at least EURO V or newer. 30% of the primary energy consumption is derived from the transport sector, with an exceptionally high rate of rise, 5% annually. 90% of the transport sector is specifically road transport. The document states total energy savings on the order of 3.22 PJ in the year 2016.

Since electrification of the transport sector no longer means providing energy from traditional fossil fuels, it also requires a higher level of interaction between the power generation and transport sector. One of the possibilities is V2G, a term defined in the late 90's with the introduction of the first EVs. To be able to implement V2G, an optimal strategy of utilizing the increasing input of RES, storage capacities of V2G EVs and balancing the generation with storage capacities is needed. Previous work by Zhang **[3]** explored integration of generation and demand side management. Zakariazadeh **[4]** proposed multi-objective scheduling method for V2G operations, an idea on which this papers' concept is based upon. Higher penetration of RES with help of V2G is described by Verzijbelrgh (**[5]**, **[6]**). Energy reduction potential in islands by Pina **[7]** is also similar to the case of Dubrovnik in terms of topology of the energy system. Overall strategies for high share of RES scenarios are compared by Cochran **[8]**.

Traditional energy planning involves defining merit-order procedure to determine the best order of generation capacities to be turned on and utilized. Typical merit-order systems include hydro, nuclear and coal plants for base load operations, and gas plants for peak loads. The introduction of RES brings the merit-order in question, as additional space for wind and solar power needs to be created at the expense of nuclear, coal and gas. This creates difficulties in determining the optimal running order **[9]**. Several mathematical models and software exist to help determine the best merit-order (**[10]**, **[11]**, **[12]**–**[15]**,**[16]**). Exergy-based analysis of an integrated energy system is of particular use when storage plays a major role in the system, or in case of inclusion of multiple energy vectors **[17]**. An important aspect of V2G is the inherent security of supply **[18]**, as was previously determined by **[19]** and **[20]** that 90% of the vehicles are stationary.

Instead, an order based on the mathematical optimization is proposed. The multi-objective goals of the optimization algorithm are minimisation of Net Present Value (NPV) of a system and maximisation of RES share in the generation mix within a 20 year scenario. Prior examples of multi-objective analysis can be found in the work of Ippolito **[21]**, Fazlollahi **[22]** and Fadaee **[23]**. Criteria for optimization are listed in the work of Østergaard [24].

Operations of such a mixed energy-transport system are best described through economics. A concept of Levelized Cost of Electricity (LCoE) is already well-established, and for this paper, a system LCoE can be defined, similar to **[25]**, while storage LCoE was investigated by Pawel **[26]**.

CASE STUDY DUBROVNIK

The case study deals with Dubrovnik and its region (***Figure Figure*** *1*), the Dubrovnik-Neretva County. From the 2011 census **[27]**, the basic statistics of the county are: area of 1781 km^2, 122870 inhabitants (2.8% of Croatia's total population), and 69 inhabitants per km^2, 5 cities, 17 municipalities and 230 settlements. All but one of the cities is located in the continental part of the County, and the County includes 6 major inhabited islands, and 1 large peninsula. With the population on the islands reaching a combined total of approximately 19000 inhabitants, the continental population is approximately 104000 permanent inhabitants. One national park is located on the island of Mljet. Main economic activities primarily stem from tourism, shipping industry, and to a minor extent, sea salt evaporation, agriculture, viticulture, olives and finally shipbuilding and masonry.

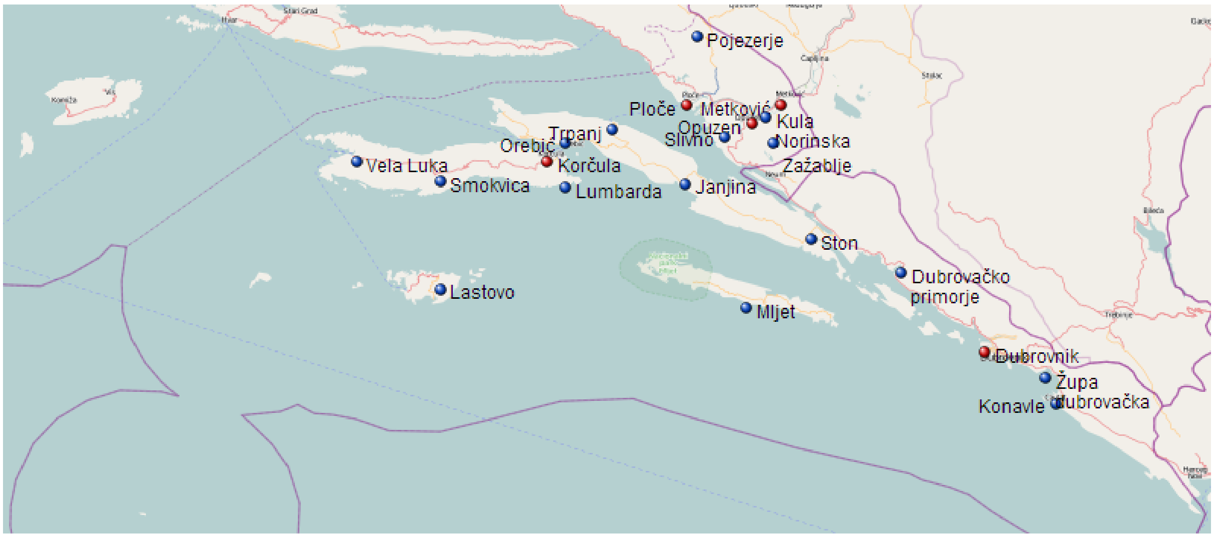

Figure 1. *Overview of Dubrovnik-Neretva County*

From the energy perspective, the County is connected to Croatian national grid by 110 kV connections over the islands and by one 220 kV connection via the neighbouring Bosnia and Herzegovina (BiH). Local energy generation capabilities include 1 hydro power plant, HE Dubrovnik, with the installed power of 2x108 MW, of which one generator provides electricity for the Croatian grid, and the other for BiH grid **[28]**. Other installations currently (2014-04) include plans for 8 wind power parks for total installation of 491 MW (36.8 MW in operation), 2 small hydro power plants of total 6.72 MW, and 4 small solar power plants of total 1 MW, none currently in operation **[29]**.

The referent year used for the scenario was obtained from the transformer substation TS Komolac for the year 2010. This substation provides power for the majority of the population in the County, and therefore is considered representative for the modelling, given actual data was obtained on a 15-minute basis for that substation for the entire year. Note that the substation had a scheduled downtime for maintenance in 2010, and the data was interpolated for the given period of 5 days (120h) in late September. Several minor outages of 1-3h during the year were also compensated by interpolating data from adjoining hours.

Generating capacity for the scenario is defined by the HE Dubrovnik, with one generator of 108 MW already in operation for the start year of the scenario in 2015. Additional generator of the same capacity will be installed in the 10th year of the scenario to accommodate future increase in demand of both the households and EVs.

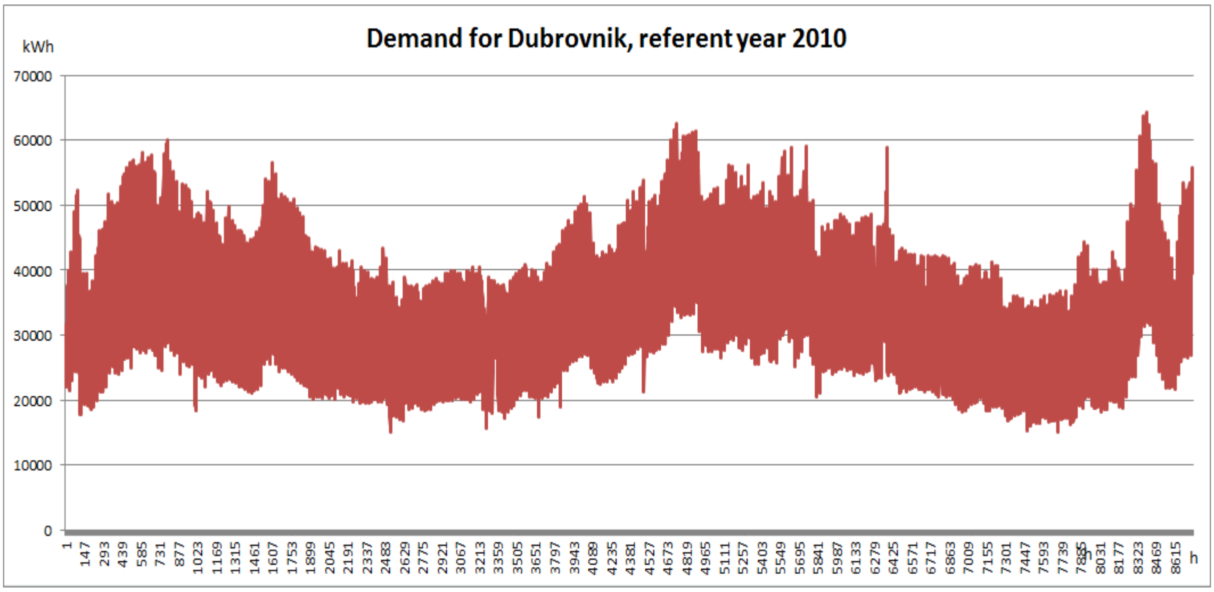

Figure 2. *Yearly electricity demand for Dubrovnik region (2010.)*

The data about electricity consumption revealed a maximum load of 64.4 MWh (***Figure 2***), and an average load of 35.5 MWh. The peak periods occur during the summer months (tourist inflow and air conditioning use), and the winter months (heating implemented mostly with electricity, either thermal accumulation or air conditioning). Annual consumption was calculated at 311.12 GWh, compared to the national electricity consumption of 4763.8 GWh in 2010, which amounts to 6.53% of total consumption. Since the region only comprises 2.89% of total national population, the difference could be explained by near complete reliance of heating/cooling demand on electricity and seasonal increase of population compared to the continental parts with higher population density and more reliance on district heating and traditional fuels.

The wind and solar resources were mapped based on data from DHMZ. Results were verified with HOMER Energy Modelling Software for wind data and PV-GIS for solar data and showed good correlation. The respective wind speed and solar irradiation curves are displayed here in ***Figure 3*** and ***Figure 4***:

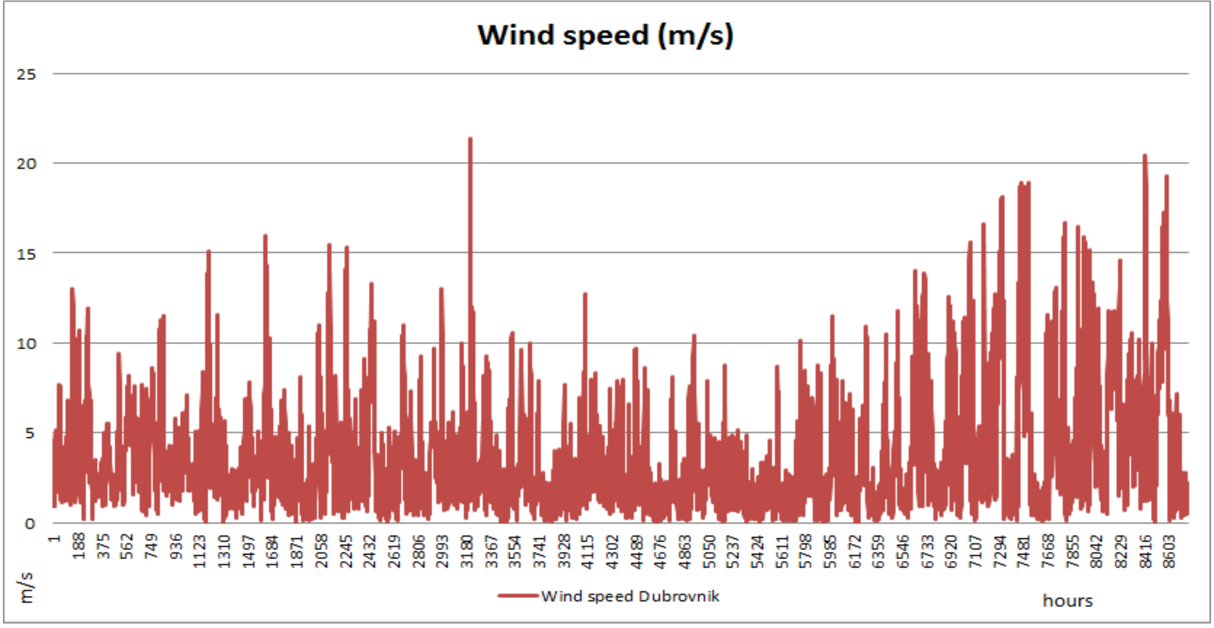

Figure 3. *Yearly wind speed measurements for Dubrovnik (h = 10m)*

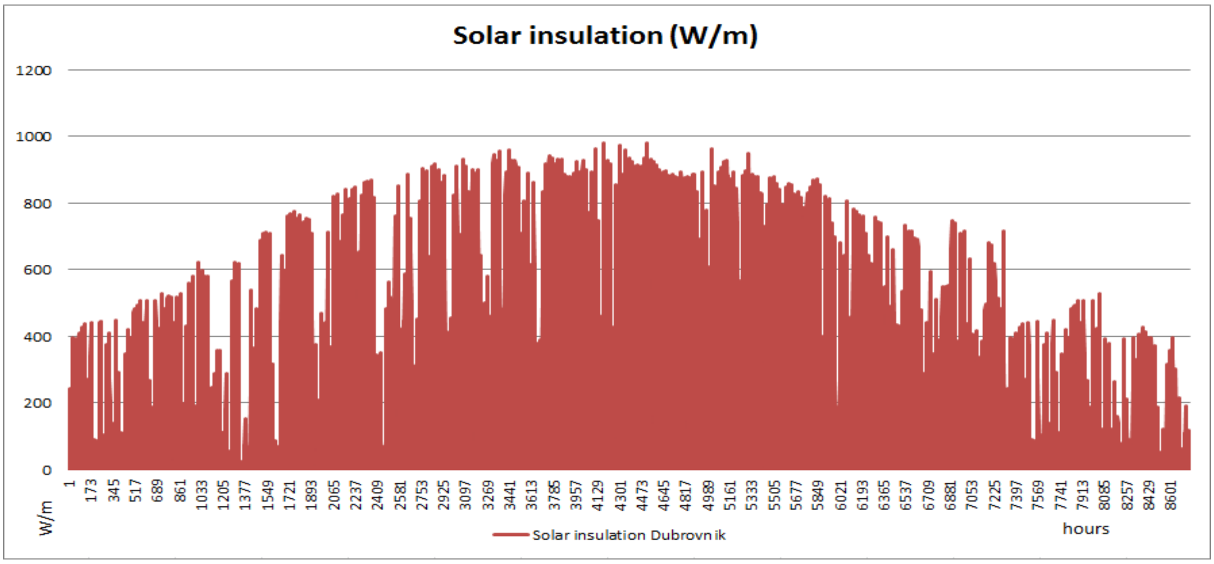

Figure 4. *Yearly solar insulation measurements for Dubrovnik*

Currently, as of 2014, there are 36.8 MW of Renewable Energy Sources (RES) installed in Dubrovnik area **[29]**, and the planned installations were increased over each time period of the energy scenario to reflect the higher penetration of intermittent sources. Given the amount of planned installations in the national Registry of RES, it was estimated that approximately 73% of wind installations would be developed by 2035, 61% by 2030 and 31% by 2020. For solar power installations, only PV was considered at a rate of 100% in 2035, 50% in 2030, and 25% in 2020. Compared to earlier work, the Registry shows approximately 100 MW less of installed power in plans, but the installed capacity was kept the same, for ease of comparison, and the fact the operating installations are already ahead of planned installed capacity, with wind power targets already being achieved in 2013 for the year 2020. The planned installation is overviewed in ***Table 1***.

Table 1. *Planned installations of RES in MW*

Base year / Scenario year	2015.	2020.	2030.	2035.
Wind power (in MW installed)	37	152	300	360
Solar power (in MW installed)	0	9	18	36

Additionally, to model the increase in population and rise in electricity demand, for the years 2020, 2030 and 2035, the demand was increased compared to the base year of 2010 in order of 3% rise annually. This amounts to total increase to 671 GWh over the period of this energy scenario, an over two-fold increase in base year consumption.

Regarding EVs, the current situation does not provide for any charging stations, and there are only a handful of registered EVs in Croatia, mostly as demonstration examples. The total number of registered vehicles in 2011 for Dubrovnik was 59674, 3.03% of the total national number of registered vehicles, 1969405. Of that number, on the area of interest (the city of Dubrovnik and the surrounding area in the radius of 15 km from the city centre) there were 22927 vehicles in 2010 and 16617 (1.36% of national number) personal vehicles. For determining the driving cycle of an average EV, a traffic study conducted by the city of Dubrovnik was used **[30]**, which sets the average daily commute distance at 45 km.

The rate of replacement of internal combustion vehicles (ICEs) for EVs is set to be linear from 2015 to 2035 and will reach 100% by the end of the scenario. That requires the replacement of 5% of the inventory yearly, which is higher than the historical replacement rate of approximately 2% yearly.

All of the EVs presented in the study meant to replace the existing ICE fleet are based on models available currently on the world market and present an average mix of the battery capacity, range and charging power values for the vehicles presented in the ***Table 2***.

Table 2. *Overview of EV models currently available in the market*

Model	Battery capacity (kWh)	Range (km)	Charging Power (kW)
Mitsubishi i-MIEV Citroen C-Zero Peugeot iOn	16	160	3.6
Nissan Leaf	24	200	3.3 / 6.6
Volvo C30 Electric	24	150	3.5
Ford Focus Electric	23	122	6.6
Honda Fit EV	20	110	6.6
Renault Zoe	22	210	6.6
Renault Fluence Z.E.	22	185	3.5
BMW i3	22	130	7.4
Smart Electric Drive	17.6	140	3.5
Chevrolet Spark EV	21.3	130	3.5
Volkswagen E-up!	18	130	3.6
Average values	20.9	153	5.0

For the technical side of V2G operations, it was decided to simulate the 24 kWh capacity Li-ion battery and Level 1 (L1) AC charger of 6.6 kW power. The range has no effect on V2G, and all of the listed models provide adequate range to sustain the assumed daily driving cycle. The discharge of the EV battery in V2G mode is constrained by the State of Charge (SoC), and the SoC is not allowed to fall below 30%. One cycle of the battery is determined as:

$$Cycle = \left(\frac{TotalEnergy}{Capacity}\right) * 0.7 \tag{1.1}$$

0.7 – represents allowed capacity to be used, set at 70%.

Charge efficiency is declared at 90%, discharge efficiency at 85%, for a round-trip efficiency of 76.5%.

The economics of the V2G operation, which will be included in the final energy system LCoE are as follows: investment costs for the utility are 25% of the battery capacity price which was assumed at 500 EUR/kWh, and the price of the L1 charger, assumed at 1500 EUR, totalling 3000 EUR per EV investment price for the energy system operator. Minimum capacity available for V2G was assumed on three levels, depending on the level of comfort and reserved range the users assume. The levels vary from 50% total battery capacity availability in case of user range anxiety, 65% in case of standard users, and 80% for aggressive V2G EV owner.

DESIGN SUPPORT FRAMEWORK – DEMAK

DeMak (also known as OCTOPUS Designer) is a framework, developed at UNIZAG-FSB, for design support that incorporates various tools that are needed for a flexible execution of a complex design process of real, practical applications. The work on *DeMak* started back in 1990 **[31]**, but recently it has been redefined to enable easy implementation of all new developments, together with the flexible graphical user interface which enables easy problem definition and problem solving.

Figure 5 shows diagram of the OCTOPUS DESIGNER components and their interaction. It is important to notice that DeMakGUI and DeMakMain are problem (model) independent. DeModel component wraps User Model components and provides prescribed IAnModel interface. This enables communication between User Model and Problem Independent components.

It is important to keep in mind that *DeMak* enables concurrent work with more than one analysis tool that have implemented IAnModel interface. That means that if some design problem demands usage of several analysis tools, they can be part of the same optimization sequence in *DeMak*.

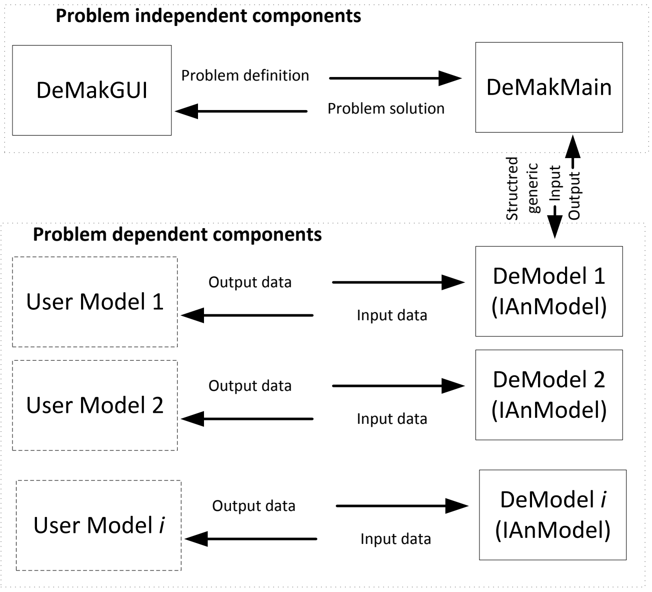

Figure 5. *DeMak components diagram*

In order to transfer data structure of an analysis model from analysis tool into generic model in most transparent manner, analysis model was envisioned to be composed from arbitrary number of systems where each system can have arbitrary number of input/output/control containers and subsystems.

Each input/output/control data container has a specific type, name and finite number of data, where each data has its own name. Type of data container depends on the analysis model that is being used. For the purpose of the research presented in this paper, light version of H2RES that implements functionalities described in previous section together with IAnModel has been developed.

DeMakMain Component is working component which encapsulates different manipulations and solution strategies which are necessary to solve real engineering design problems (e.g. problem decomposition, surrogate modelling hybrid optimization solvers). Some recent developments and application of decomposition and surrogate modelling ship structural design are presented in Zanic et al. **[32]** and Prebeg et al. **[33]**.

Implemented optimization methods includes: multi-objective genetic algorithms, multi-objective particle swarm, sequential adaptive generation of non-dominated designs, sequential linear programing, and sequential quadratic programming. Those optimization methods can be combined within *DeMak* to form a hybrid solver where certain optimization algorithm is used in the part of design process where it is the most suitable. For example, in the design space where multiple local extremes exits, the optimization could start with genetic algorithms (good global search capabilities), followed with the sequential linear or quadratic programming (very fast local search), which would start from the previously found promising designs.

DeMak graphical user interface (GUI) enables designer's flexible communication with DeMakMain component in the form of interactive input definitions and output visualizations.

METHODOLOGY

Problem description

Total multi-objective optimization problem can be written as:

$$\begin{gathered}
\begin{matrix} \min NPV \\ \min \overline{NPV} \\ \max RESSh \end{matrix} \quad \left(P_{Ni}, \Delta P_i, r_{i,t}\right) \\
s.t. \\
\sum_{i=1}^{N_p} e_{i,t}\left(P_{Ni}, \Delta P_i, r_{i,t}\right) \geq D_t \\
t = 1,2,..24 \cdot 365 \cdot 20 \\
i = 1,2..N_p
\end{gathered} \tag{1.2}$$

where:

P_{Ni} - Nominal power of power plant *i* (in starting year)

ΔP_i – Yearly increase of nominal power of power plant *i*

$r_{i,t}$ – regulation of power plant *i* in a hour *t*

NPV – Net present value of designed energy system

$\overline{NPV}$ – Net present value normalized by the total energy produced to cover demand

RESSh – Ratio of energy produced by the RES in designed energy system

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.

Practical solution for an energy system design is usually obtained using the merit order approach similar to the one used in H2RES (see ***Problem solution 1***). That kind of approach usually gives satisfactory result in energy systems with high RES share; however it still leaves space for possible improvements. The other approach, given as ***Problem solution 2*** is part of ongoing research, offers significant improvement for energy systems with available storage capacity from EV.

Problem solution 1 - H2RES merit order

For practical application, total problem described in above can be solved by decomposing the total problem on the Global and Local problems as given by the next expressions:

$$
\begin{array}{ll}
\begin{array}{c} Level\ 0 \\ (Global\ problem) \end{array} &
\begin{array}{c}
\begin{array}{l} min\ NPV \\ min\ \overline{NPV} \quad \left(P_{Ni}, \Delta P_i,\ {}^1e_{i,t}\right) \\ max\ RESH \end{array} \\
s.t. \\
E_t = \sum_{i}^{N_P} {}^1e_{i,t} \geq D_t \\
t = 1,2,..24 \cdot 365 \cdot 20;\ i = 1,2..N_p
\end{array}
\end{array}
\tag{1.3}
$$

$$
\begin{array}{ll}
\begin{array}{c} Level\ 1 \\ Regulation\ (T=1) \end{array} &
\begin{array}{c}
e_{i,t} = \left(\ {}^0P_{Ni},\ {}^0\Delta P_i, r_{i,t}\right) \left|
\begin{array}{l}
D_t < \left(\sum_{i}^{N_{RES}} e_{i,t} + \sum_{i}^{N_B} e_{i,t}\right); \text{store energy} \\
D_t > \left(\sum_{i}^{N_{RES}} e_{i,t} + \sum_{i}^{N_B} e_{i,t}\right); \text{empty storage} \\
D_t > \left(\sum_{i}^{N_{RES}} e_{i,t} + \sum_{i}^{N_B} e_{i,t} + \sum_{i}^{N_{Stor}} e_{i,t}\right);\ \text{peak powerplant}
\end{array}\right. \\
t = 1,2,..24 \cdot 365 \cdot 20;\ i = 1,2..N_p
\end{array}
\end{array}
\tag{1.4}
$$

where:
Et – Energy produced by Energy system in time t
T – Interval in which local problem is solved
$r_{i,t}$ – regulation of power plant i in a hour t

Global problem is multi-objective optimization problem where optimization variables do not include the regulation variables as in original problem. Optimization variables still includes $P_{Ni}, \Delta P_i$, while ${}^1e_{i,t}$ is output value of Level 1 problem where it is determined using the merit order. On the local level, coverage of the demand for each hour is assured. It is important to notice that the period T of local problem is one hour, which means that total number of local problems is the total number of hours for which the energy system is designed (24*365*20=7300 for Dubrovnik case).

Problem solution 2- Local day (24h) based optimization
Similar as in the first approach, the original problem is decomposed on the Global and Local problems as given by the next expression.

$$
\begin{array}{ll}
\begin{array}{c} Level\ 0 \\ (Global\ problem) \end{array} &
\begin{array}{c}
\begin{array}{l} min\ NPV \\ min\ \overline{NPV} \quad \left(P_{Ni}, \Delta P_i,\ {}^1e_{i,t}\right) \\ max\ RESH \end{array} \\
E_t = \sum_{i}^{N_P} {}^1e_{i,t} \geq D_t \\
t = 1,2,..24 \cdot 365 \cdot 20;\ i = 1,2..N_p
\end{array}
\end{array}
\tag{1.5.}
$$

$$
\begin{array}{ll}
\begin{array}{c} Level\ 1 \\ Regulation\ (T=24) \end{array} &
\begin{array}{c}
min \sum_{i,t}^{N_P,24} f_{i,t} \quad \left(\ {}^0P_{Ni},\ {}^0\Delta P_i, r_{i,t}\right) \\
s.t. \\
\sum_{i}^{N_P} e_{i,t} = \left(\ {}^0P_{Ni},\ {}^0\Delta P_i, r_{i,t}\right) \geq D_t \\
t = 1,2,..24;\ i = 1,2..N_p
\end{array}
\end{array}
\tag{1.6.}
$$

The global problem 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 is mostly determined by their day-based obligations. The same applies for the electric energy demand.

The definition of solution sequence in *DeMak* is shown in ***Figure 6***. Global optimization problem, with multi-objective particle swarm optimizer (MOPSO HC) calls DayOptJob solution sequence in which 7300 days are solved. The definition of this practically applicable sequence includes use of H2RES merit order where it can satisfy current day demand. The reason for that is the merit order efficiency with respect to the computation time necessary for local optimization problem solution. Local 24-hour optimization problem takes from several hundred to several thousands more computations than the merit order.

Due to that, as can be seen in the diagram in ***Figure 6***, for each new day in which regulation variables needs to be determined, simulation with merit order is used first, if merit order simulation (SimMerit) can satisfy the demands, the regulation variables determined by the merit order are saved for that day, and the sequence will advance to the next day. If the merit order cannot satisfy the demand, simulation that test maximal theoretical production of the energy system with storage used (Sim24hMaxStor). This type of the simulation is necessary in order to prevent local level optimizer to spend time on the solution that is impossible to solve. Fortunately this type of simulation is not overly difficult to create since it just collects all the regulation variables, including the storage regulation variables, to max production for hours in which maximal production of non-storage power plants is smaller than demand. If this kind of solution cannot satisfy the demands, there is no need to try to use optimization method to find optimal regulation variables. In that case, max production regulation variables are saved for the current day and simulation sequence advances to the next day. In that way global problem will still receive the proper information on level of inadequacy of the demand satisfaction while a significant time will be spared because optimizer will not try to solve the local problem that is actually impossible to solve.

If the Sim24hMaxStor produces feasible solution NLOpt optimization library (SQP algorithm) is used to find optimal values of regulation variables.

It is important to mention that implemented solution sequence on the local level does not guaranty globally optimal solution, however it does guaranty that minimal possible setup regarding total installed power of each power plant will be found.

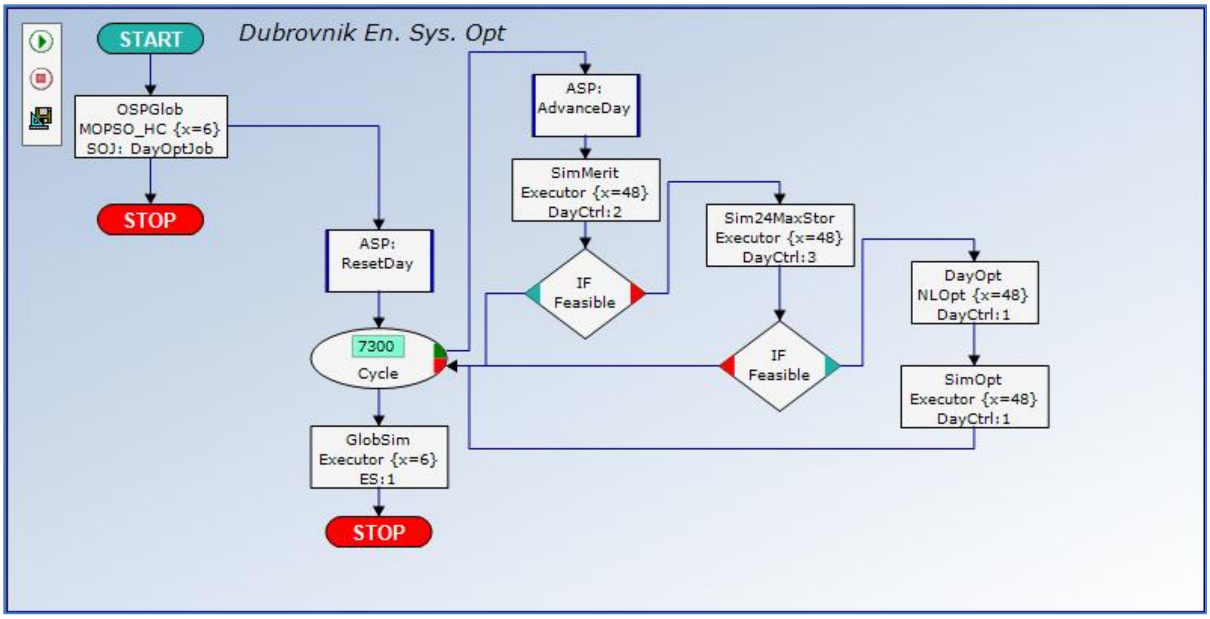

Figure 6. *Problem solution in DeMak*

RESULTS

The following is the graph representation of obtained non-dominated solutions for Global problems displayed in *DeMak* graphical interface. ***Figure 7*** and ***Figure 8*** display the Pareto solutions in attribute/objective space where the three used objectives (min NPV, min $\overline{NPV}$, max $RESSh$) are on x y z coordinate axis. In order to position presented solutions in 3D space, the figures also show projections of those solutions on 2D planes (in black). By comparison of the two fronts obtained by two different problem solution sequences, it is evident that the non-dominated solutions of second problem solution clearly outperforms and actually dominates on non-dominated solutions generated by the ***Problem solution 1*** sequence. At the same time ***Figure 9*** and ***Figure 10*** show the non-dominated solution in a design space where nominal power installations of hydro, wind and solar capacities are on x y z coordinate axes.

Some of the interesting information that can be seen on those figures is that minimum possible install power of the hydro power plant (the only non-RES power plant in the case study) for the ***Problem solution 1*** sequence is 113 MW, while for the ***Problem solution 2*** it is 89.3 MW. The other interesting information is that installed power of solar power plant has converged to the minimal possible installed power (25 MW) for almost all non-dominated solutions. This also indicates that wind energy have much higher influence on RESSh objective then solar power plant since wind energy is still much more economically viable then the solar energy.

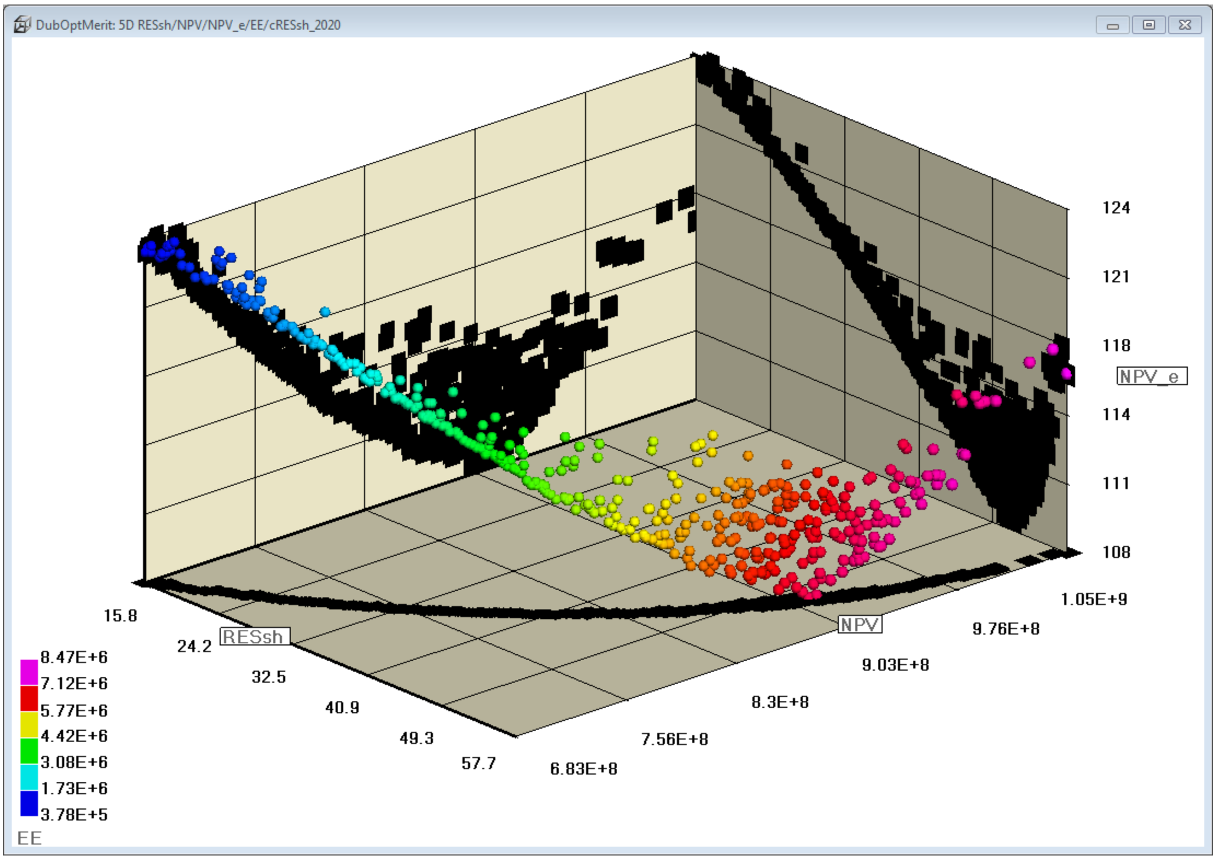

Figure 7. *Non-dominated solutions obtained by Problem solution 1 in attribute space*

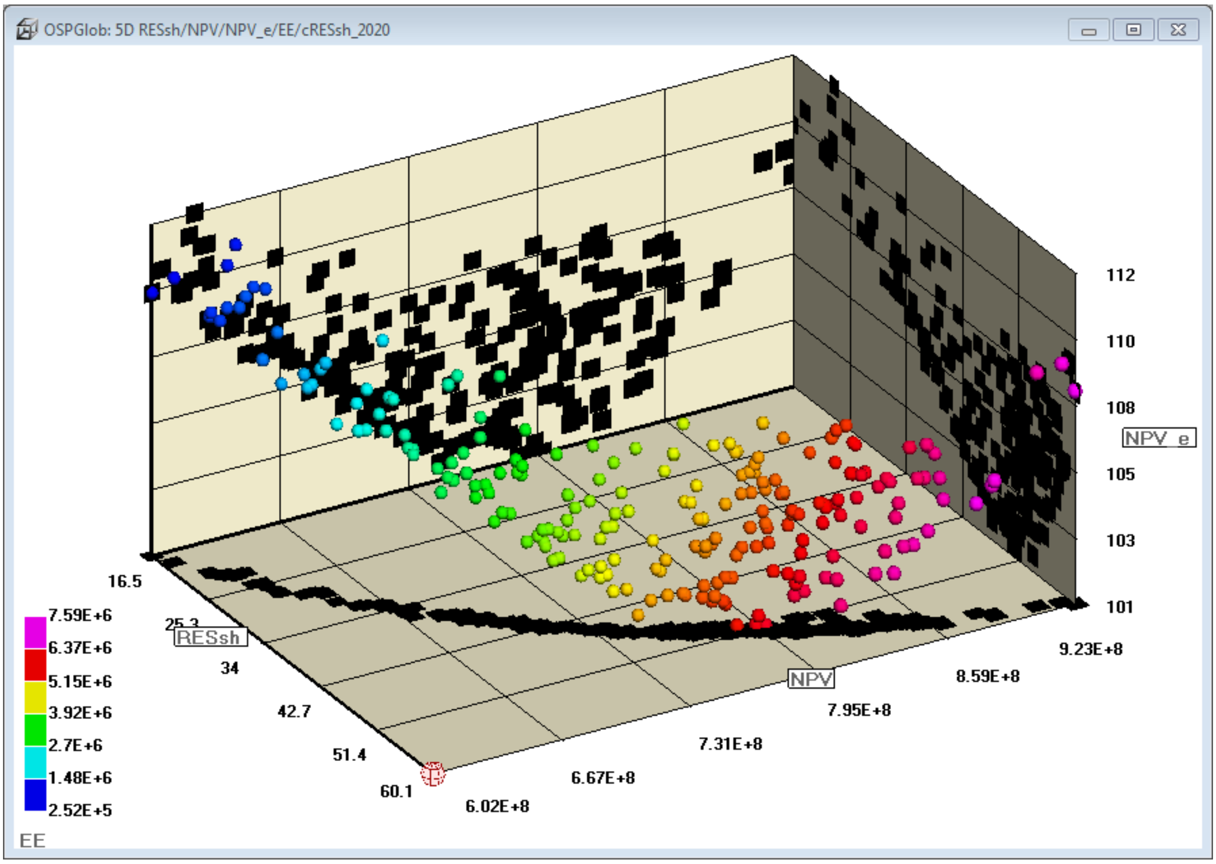

Figure 8. *Non-dominated solutions obtained by Problem solution 2 in attribute space*

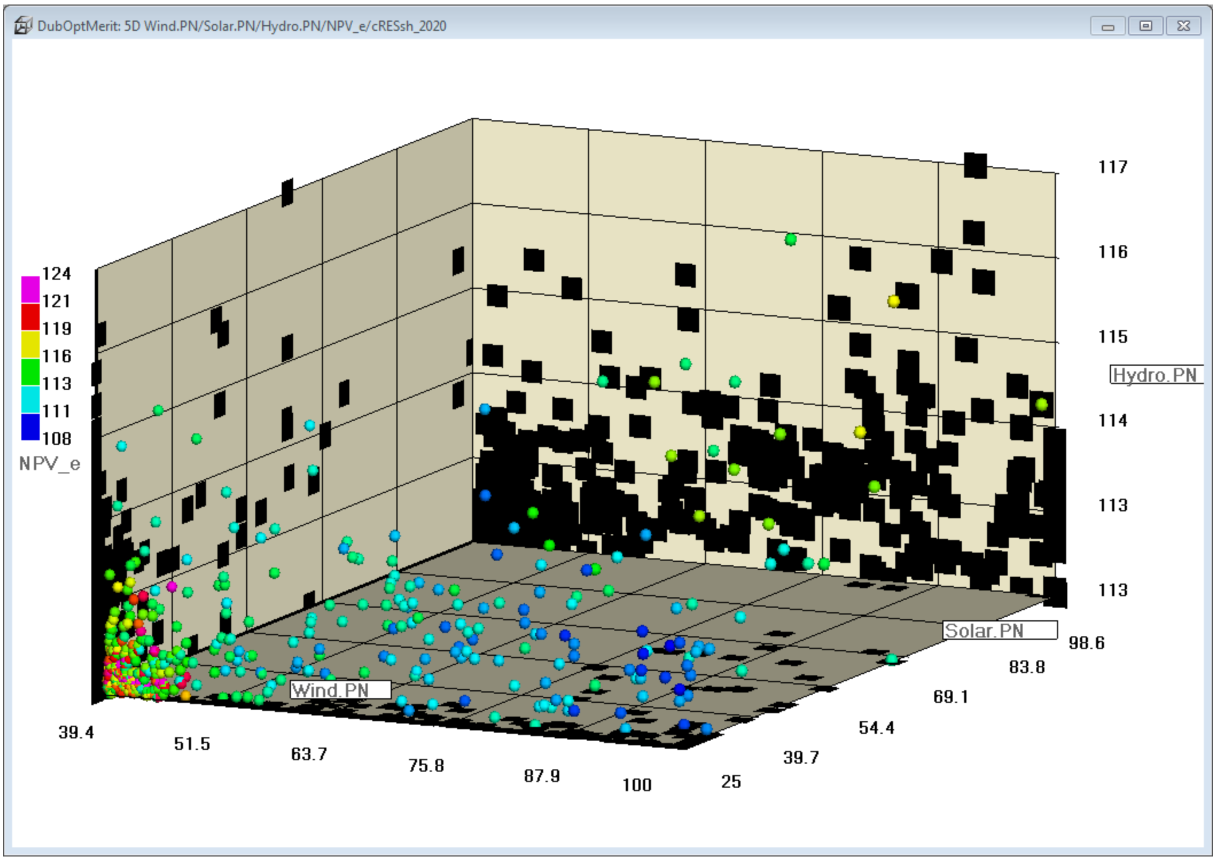

Figure 9. *Non-dominated solutions obtained by Problem solution 1 in design space*

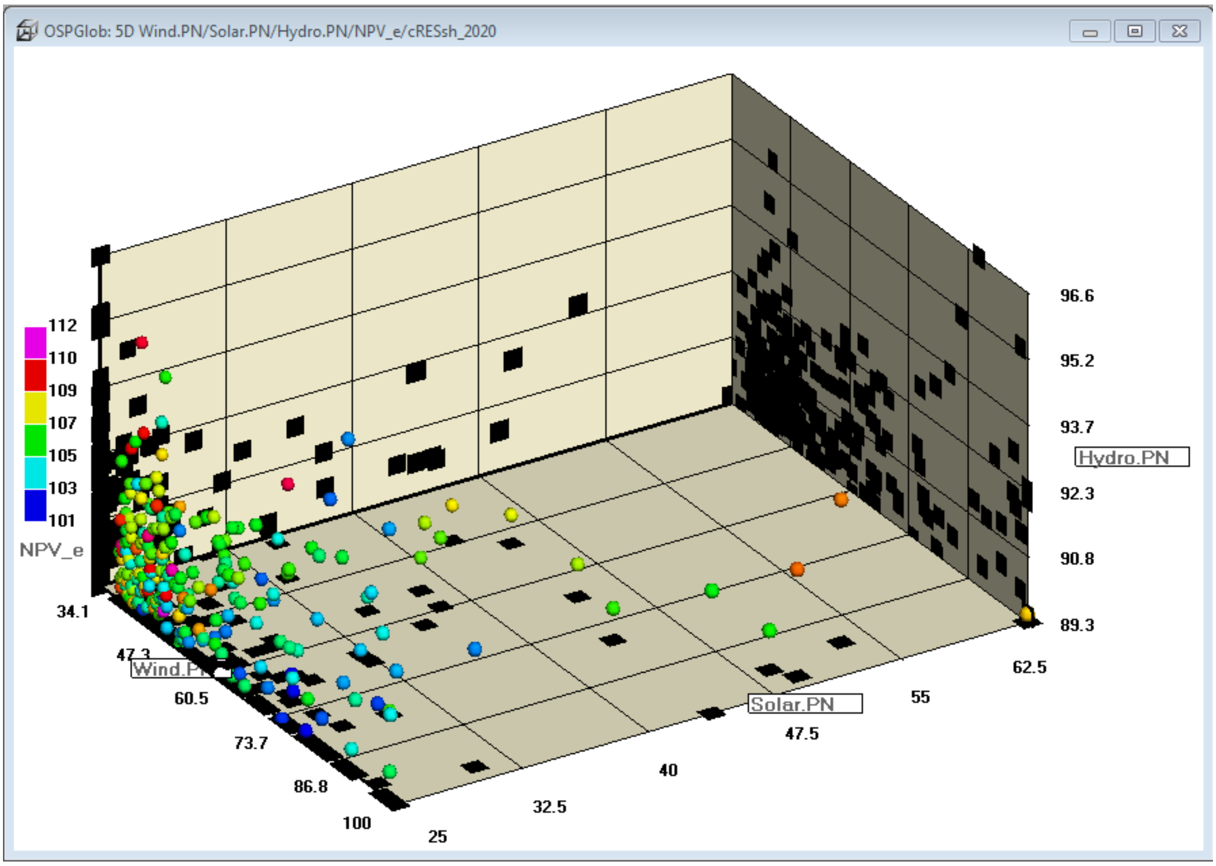

Figure 10. *Non-dominated solutions obtained by Problem solution 2 in design space*

The reason why ***Problem solution 2*** outperforms ***Problem solution 1*** is illustrated in ***Figure 11*** and ***Figure 12*** which shows 24 hours of the day 3634, which turns to be the critical day in the entire scenario period. Those figures show how the corresponding minimum $\overline{NPV}$ design satisfies demand (red line). In both figures the produced energy is exactly the same as demand, while in ***Problem solution 2*** EV battery storage has enough capacity (blue line) to produce energy in a period between hour 87233 and 87240 to cover difference between demand and hydro power plant. The reason why this period is critical is because the period between hour 87233 and 87240 has negligible electricity production from RES, so it is only possible to produce energy from hydro power plant (green line) and EV storage (magenta line). The problem of ***Problem solution 1*** is that it starts to empty storage too early, while the ***Problem solution 2*** empties the storage exactly in the hours where it is needed the most. This is the reason why designs from problem solution needs less hydro power energy.

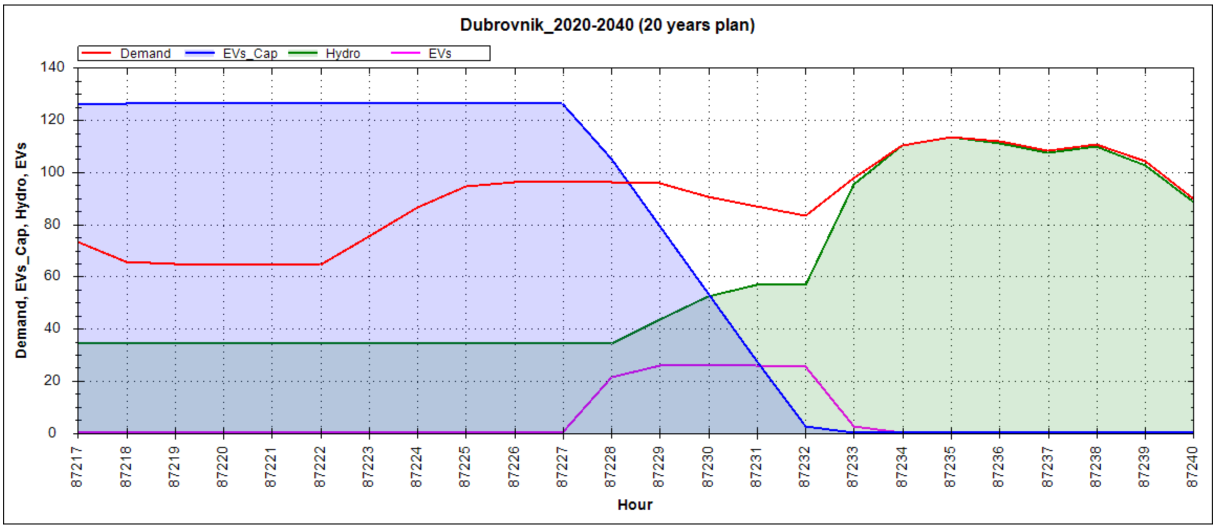

Figure 11. *Day 3634 –Problem solution 1- Min* $\overline{NPV}$ *design*

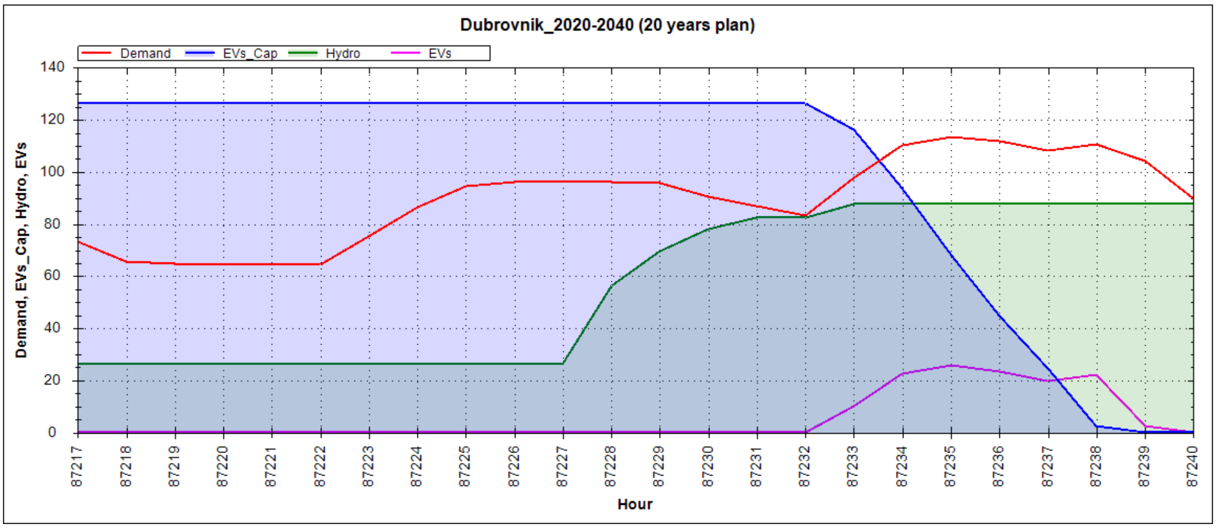

Figure 12. *Day 3634 –Problem solution 2- Min* $\overline{NPV}$ *design*

CONCLUSION

The use of the 24-hour optimization problem on the local level clearly outperforms hour-based merit order with respect to the extreme values of all used objectives, as well as with the entire non-dominated frontier. However, merit order approach is several hundred to several thousand times less time consuming. Due to that, practical implementation of the local level solution sequence uses 24-hour optimization problem only when merit order cannot satisfy all of the demands.

It is necessary to use stable optimization method that guaranties the solution for the local level problem since a huge number of local problems need to be solved for each global problem variant.

Acknowledgment

It is gratefully acknowledged that this work has been supported by the Croatian Science Foundation through the “Optimization of Renewable Electricity Generation Systems Connected in a Microgrid” collaborative research project, grant No. HRZZ 08/40. and "ICTaided integration of Electric Vehicles into the Energy Systems with a high share of Renewable Energy Sources" collaborative research project grant No. 09/128.

BIBLIOGRAPHY

[1] "EU Directive 2009/28/EC." [Online]. Available: http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0028.

[2] "Croatian National Energy Action Plan for RES up to 2020." [Online]. Available: http://ec.europa.eu/energy/renewables/transparency_platform/doc/dir_2009_0028_action_plan_croatia.zip.

[3] 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.

[4] A. Zakariazadeh, S. Jadid, and P. Siano, "Multi-objective scheduling of electric vehicles in smart distribution system," *Energy Convers. Manag.*, vol. 79, pp. 43–53, Mar. 2014.

[5] R. Verzijlbergh, C. Brancucci Martínez-Anido, Z. Lukszo, and L. de Vries, "Does controlled electric vehicle charging substitute cross-border transmission capacity?," *Appl. Energy*, vol. 120, pp. 169–180, May 2014.

[6] R. A. Verzijlbergh, Z. Lukszo, J. G. Slootweg, and M. D. Ilic, "The impact of controlled electric vehicle charging on residential low voltage networks," in *2011 International Conference on Networking, Sensing and Control*, 2011, pp. 14–19.

[7] A. Pina, P. Baptista, C. Silva, and P. Ferrão, "Energy reduction potential from the shift to electric vehicles: The Flores island case study," *Energy Policy*, vol. 67, pp. 37–47, Apr. 2014.

[8] J. Cochran, T. Mai, and M. Bazilian, "Meta-analysis of high penetration renewable energy scenarios," *Renew. Sustain. Energy Rev.*, vol. 29, pp. 246–253, Jan. 2014.

[9] R. Prakash and I. K. Bhat, "A figure of merit for evaluating sustainability of renewable energy systems," *Renew. Sustain. Energy Rev.*, vol. 14, no. 6, pp. 1640–1643, Aug. 2010.

[10] D. Connolly, H. Lund, B. 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.

[11] 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.

[12] G. Krajačić, N. Duić, 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.

[13] G. Krajačić, N. Duić, and M. da G. Carvalho, “How to achieve a 100% RES electricity supply for Portugal?,” *Appl. Energy*, vol. 88, no. 2, pp. 508–517, Feb. 2011.

[14] P. Fowler, G. Krajačić, D. Lončar, and N. Duić, “Modeling the energy potential of biomass – H2RES,” *Int. J. Hydrogen Energy*, vol. 34, no. 16, pp. 7027–7040, Aug. 2009.

[15] G. Krajačić, R. Martins, A. Busuttil, N. Duić, 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.

[16] A. Pina, C. A. Silva, and P. Ferrão, “High-resolution modeling framework for planning electricity systems with high penetration of renewables,” *Appl. Energy*, vol. 112, pp. 215–223, Dec. 2013.

[17] N. Jain and A. G. Alleyne, “A framework for the optimization of integrated energy systems,” *Appl. Therm. Eng.*, vol. 48, pp. 495–505, Dec. 2012.

[18] L. E. Bremermann, M. Matos, J. A. P. Lopes, and M. Rosa, “Electric vehicle models for evaluating the security of supply,” *Electr. Power Syst. Res.*, vol. 111, pp. 32–39, Jun. 2014.

[19] 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.

[20] W. Kempton and J. Tomić, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” *J. Power Sources*, vol. 144, no. 1, pp. 268–279, Jun. 2005.

[21] 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.

[22] S. Fazlollahi, P. Mandel, G. Becker, and F. Maréchal, “Methods for multi-objective investment and operating optimization of complex energy systems,” *Energy*, vol. 45, no. 1, pp. 12–22, Sep. 2012.

[23] M. Fadaee and M. A. M. Radzi, “Multi-objective optimization of a stand-alone hybrid renewable energy system by using evolutionary algorithms: A review,” *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 3364–3369, Jun. 2012.

[24] P. A. Østergaard, “Reviewing optimisation criteria for energy systems analyses of renewable energy integration,” *Energy*, vol. 34, no. 9, pp. 1236–1245, Sep. 2009.

[25] F. Ueckerdt, L. Hirth, G. Luderer, and O. Edenhofer, “System LCOE: What are the costs of variable renewables?,” *Energy*, vol. 63, pp. 61–75, 2013.

[26] 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.

[27] “2011 Census RH.” [Online]. Available: http://www.dzs.hr/Hrv/censuses/census2011/censuslogo.htm.

[28] “HOPS.” [Online]. Available: http://www.hops.hr/wps/portal/hr/web/hees/podaci/shema.

[29] “OIEKPP-MINGORP.” [Online]. Available: http://oie.mingorp.hr/default.aspx?id=24.

[30] “Traffic study, City of Dubrovnik.”

[31] Zanic, V., Grubisic, I., and Trincas G., “Multiattribute decision making system based on random generation of nondominated solutions,” in *5th International Symposium on the Practical Design of Ships and Mobile Units (PRADS)*, 1992, p. 18.

[32] V. Zanic, J. Andric, P. Prebeg, and P. Žanić, V.; Andrić, J.; Prebeg, “Design synthesis of complex ship structures,” *Ships Offshore Struct.*, vol. 8, no. 3–4, pp. 383–403, Jun. 2013.

[33] 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.