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GENERATION SCHEDULING IN POWER SYSTEMS WITH HIGH PENETRATION OF RENEWABLE ENERGY

SUMMARY

Share of renewable energy sources increased rapidly over last two decades primary as wind and solar power plants. Their increase was driven by governmental subsidies and priority access and dispatch regarding conventional units. Wind and solar power plants are inflexible sources because their generation depends on exterior, weather conditions and they cannot be controlled as conventional units. This paper will define term power system flexibility and provide an insight into flexibility of conventional and modern power systems. Detailed mathematical model of power system and all its components has been created and explained. Modeling has been executed as mixed integer linear program using Fico Xpress optimization suite. Using those models, flexibility analyses of power systems with different renewable energy sources share has been conducted.

Key words: Mixed Integer Linear Programming, Power System Flexibility, Renewable Energy Sources, Unit Commitment, Wind Power Plants

1. INTRODUCTION

Penetration of renewable energy sources in power system have numerous advantages for the society in general, such as: lower energy costs, greenhouse gas emission decrease, decrease in dependence on fossil fuels, new vacancies [1] etc. But from the technical point of view, it changes conventional power system paradigm where power plants were controllable and used to cover demand variations and equipment failures. If renewable energy sources take higher share in total installed power, it effectively means increase in power variations and lower share of controllable units. Power system operators and planners must prepare for such transition in order to maintain continuous and reliable power supply. First step is do determine the cumulative impact of renewable source on power system costs and behavior through certain period. Second step should be testing of novel technologies in order to lower the costs and increase reliability. For mentioned reason, this paper aims to build a mathematical model of a power system and use the created model for analyzing the system flexibility with different shares of intermittent renewable energy resources. The paper is divided into three main parts. The first section briefly explains the characteristics of the power system now and in the past, and gives insight into further development of the system. Section also explains the concept of flexibility and applies it to the entire system and its components. The second part focuses on the development of mathematical model of the power system whose goal is optimization of generation scheduling minimizing operational costs. Final chapter tests performance of the model on different power systems. Used systems are constructed of thermal power, hydropower, renewable energy, energy storage and demand response. It analyzes the behavior of various power systems by adding new wind farms, photovoltaic power plants, energy storage and demand response into calculation. Finally, results are summarized, systems are evaluated regarding flexibility.

2. FLEXIBLITY

Power consumption is time-varying value observing different timescales: day (high consumption at daytime, low at night), week (higher consumption at work days then weekends), year (seasonal fluctuations) and long-term (in general, demand increase every year). In conventional vertically integrated power system, power system operator must commit units to cover total demand. Base load is usually covered by highly inflexible units such as nuclear and run-of-river hydro power plants, while intermediate load is usually covered by fossil fuel (coal and oil) power plants and hydro power plants with low accumulation. Peak load is covered by flexible units such as hydro power plants with large accumulation, pump storage or gas fueled thermal power plants.

Flexibility of units is determined by their technical parameters:

- Technical minimum,

- Ramping,
- Minimum up time,
- Minimum down time,
- Maximum generation.

Another flexibility barrier is the cost of generation. Each unit have several costs associated with its generation:

- No-load cost,
- Variable cost,
- Startup cost,
- Greenhouse gas emission cost.

Nuclear power plants have inadequate technical parameters for flexibility, high startup and low variable cost. Therefore, once when they are started their power is maintained fixed. Hydro power plants possess good technical flexibly parameters and low startup costs, so if there is sufficient accumulation they are generally driven in load-following regime. Thermal power plants have better technical parameters for flexibility then nuclear but lower then hydro power plants. Coal and oil have relatively high startup costs and low variable cost, whereas gas have low startup cost and high variable cost. In other words, coal and oil units are used as base or intermediate units and gas as peak units.

Due to variability and demand forecast mistakes each power system must have sufficient flexibility to maintain generation and load balance. In order to be sure that the system will be balanced in each time period sufficient reserves must be committed. Eventhough demand forecast are getting better and better and mistakes are very low, still we can model them with normal probability function with average value zero and standard deviation of 1% of current demand. If range of 3σ is considered, 99,7% of load deviations will be covered. Another big issue is probability of failure of power system equipment such as generators and lines. Simple way to address this issue is to incorporate the size of the biggest generator in the equations for reserve calculation. Equations

$$R_{Tup}(t) = \sqrt{(3 * \sigma_d(t))^2 + (P_{Gmax}(t))\char`^2}, \qquad t \in [1, N_t \tag{1}$$

$$R_{Tdn}(t) = 3 * \sigma_d(t), \qquad t \in [1, N_t] \tag{2}$$

- R_{Tup}, R_{Tdn} – Up and Down reserve of traditional power system,
- σ_d – Standard deviation of load,
- P_{Gmax} – Installed power of the biggest generator.

Increasing share of variable renewable energy sources such as wind, run-of-river hydro, solar, waves etc. increase the flexibility requirements as well. Solar and wind power plants are the most widespread renewable energy technology and they will be used as representatives for the group. Neither solar nor wind do not have storage capability, so they must generate and inject power into the grid when meteorological conditions are met. Wind variability can be observed on different timescales. Statistical analyses of long-term observations indicate certain regularity due to seasonal methodological patterns. On second timescale, wind speed and direction variations are notable, but they are mitigated through relatively slow wind turbine response. The biggest problem for the system are wind speed and direction variations on minute timescale because the system must have enough flexible units to change their direction when wind turbines change their generation. Variations of solar irradiation can be divided into those caused by Earth's movement around the Sun and those caused by atmospheric dispersion. First ones are easily predictable (both daily and seasonally), but cloud movements through atmosphere are not and they bring forecast errors into prediction of output power generation of solar panels. In order to take into account both wind and solar prediction errors Eq. 1. and 2. should be modified with standard deviations of wind and solar generation to equations:

$$R_{Mup}(t) = \sqrt{(3 * \sigma_d(t))^2 + (3{,}5 * \sigma_w(t))^2 + + \left(3{,}5 * \sigma_{pv}(t)\right)^2 + (P_{Gmax}(t} \quad (3)$$

$$R_{Mdn}(t) = \sqrt{(3 * \sigma_d(t))^2 + (3{,}5 * \sigma_w(t))^2 + + \left(3{,}5 * \sigma_{pv}(t)\right)^2}, \quad t \in [1, N_t] \quad (4)$$

- R_{Mup}, R_{Mdn} – Up and Down reserve of modern power system,
- σ_d, σ_w, σ_{pv} – Standard deviation of load, wind and solar generation,
- P_{Gmax} – Installed power of the biggest generator.

Forecast errors are increasing as period of forecasting increases. In this paper, 24 hour ahead forecasts are taken as inputs and reserve is therefore modeled in a way that it increases every hour. In the last observed hour, reserve is 10% higher then without the increase.

Power system flexibility can be increased through:

- Reconstruction of existing generators (updating their technical characteristics, lower technical minimum, faster ramping, shorter up and down times…),
- Investment in new flexible generators (gas turbines),
- Investment in new interconnectors (adjacent power systems coupling),
- Integration of energy storage technologies,
- Activation of demand, enabling demand response…

Energy storage technology are gaining a lot of attention last few years, mostly as a direct consequence of RES integration and increased system flexibility needs. Energy storage systems increase total system efficiency and can make some of the peak plants unnecessary. Still, energy storage systems are too expensive to be cost effective. One why is to subside them in a similar manner as governments created subsidies for RES technologies. On competitive electricity market energy storage technologies should be equal to production units and should be able to provide different services (reserves, voltage regulation, black start etc.). Similar to energy storage, demand response could be used to provide flexibility to power system. The highest investment to enable demand response is investment in ICT equipment to create conditions for automatic response of flexible demand.

3. MATHEMATICAL MODEL

Mixed integer linear program has been created in Fico Xpress optimization suite [2]. Modeling is divided into several parts: definition of variables, initialization of input parameters, modelling of constraints, objective functions and verification through results. Input parameters have been read from excel file where the output results are printed and graphically processed. Observed power system is composed of

N_i thermal power plants (fossil and nuclear), N_{ih} hydro power plants and pump storage, wind turbines, photovoltaics, battery storage systems and demand response. Each of the technologies have specific constraints modeled so the system is as close to real as possible. In each time period N_t power generation and demand must be balanced. For more information, similar modeling can be found in [3],[4], and [5].

3.1. Objective function

Objective function is summation of thermal and hydro generation costs. Thermal power plant costs are given through Eq. (5) as summation of five parts:

- Startup costs,
- Shut-down costs,
- No-load fixed costs,
- Variable fuel costs, and
- Greenhouse gas emissions costs.

$$C_{TE}(t,i) = v_{on}(t,i) * C_{start}(i) + v_{off}(t,i) * C_{shut}(i) + A(i) * n(t,i) + B(i) * P(t,i) + Em(t,i) * Em_c(i), t \in [1, N_t], i \in [1, N_i] \quad (5)$$

Vector n shows how many thermal power plants from each of the subgroup (nuclear, coal, gas CCGT, gas OCGT) is online, whereas vectors v_{on} and v_{off} show how many thermal power plants is startup or shutdown each discrete time step.

$$v_{on}(t,i) \geq n(t,i) - n(t-1,i) \tag{6}$$

$$v_{off}(t,i) \geq n(t-1,i) - n(t,i) \tag{7}$$

Greenhouse gas emissions have two parts, one concerning startup emissions and variable emissions connected with each new generated unit of electricity:

$$Em(t,i) \geq v_{on}(t,i) * Em_{rstart}(i) + P(t,i) * Em_r(i), \qquad t \in [1, N_t], i \in [1, N_{ih}] \tag{8}$$

Hydro power plant costs are composed of fixed and variable costs, where variable cost is concerning maintenance not fuel cost as with thermal power plants.

$$C_{HE}(t,i) = A_h(i) * n_h(t,i) + B_h(i) * P_h(t,i), \qquad t \in [1, N_t], i \in [1, N_{ih}] \tag{9}$$

Two aditional terms were added to objective function in Eq. 10 in order to ensure feasiblity of the model. Variables e_{minus} and e_{plus} represent lack and surplus of power within the system.

$$f_{cilj}{}^{min} = \sum_{t=1}^{Nt} \left\{ \sum_{i=1}^{Ni} [C_{TE}(t,i)] + \sum_{i=1}^{Nih} [C_{HE}(t,i)] + e_{minus}(t) * C_{shed} + e_{plus}(t) * C_{ove} \right. \tag{10}$$

2.2. System constraints

There are two main constraints in observed power system: power generation-demand balance represented with Eq. 11, and reserve provision-requirements balance for up and down reserve represented with Eq. 12 and 13. Terms in Eq. 11 from left to right: thermal power plants generation, hydro power plants generation (minus potential pumping of pump storage facilities), wind generation, photovoltaics generation, battery charging/discharging power, feasibility variables (up and down) and on the right-hand side total system demand.

$$\sum_{i=1}^{Ni} P(t,i) + \sum_{i=1}^{Nih} [P_h(t,i) - P_p(t,i)] + w(t) + pv(t) + P_b(t) + e_{minus}(t) - e_{plus}(t) = . \qquad t \in [1, N_t] \tag{11}$$

$$\sum_{i=1}^{Ni} r_{up}(t,i) \geq R_{up}(t), \qquad t \in [1, N_t] \tag{12}$$

$$\sum_{i=1}^{Ni} r_{dn}(t,i) \geq R_{dn}(t), \qquad t \in [1, N_t] \tag{13}$$

Please note that only one type of reserves has been observed due to simplicity.

2.3. Component constraints

This Subsection is going to define constraints for each of the technologies observed in model.

Eq. 14 represents generators technical minimum and maximum generation constraint (vector *n(t,i)* is number of online units in the system). In Eq. 15 total number of thermal generators has been defined, while Eq. 16 and 17 define number of units started up and shut down each time step.

$$n(t,i) * P_{max}(i) \geq P(t,i) \geq n(t,i) * P_{min}(i), \qquad t \in [1, N_t], i \in [1, N_i] \tag{14}$$

$$n(t,i) \leq G(i), \qquad t \in [1, N_t], i \in [1, N_i] \tag{15}$$

$$v_{on}(t,i) \leq n(\tau,i), \qquad \tau \in \left[t+1, \min\left(t + T_{up}(i) - 1, N_t\right)\right], \qquad t \in [1, N_t - 1], i \in [1, N_i] \tag{16}$$

$$v_{off}(t,i) \leq G(i) - n(\tau,i), \qquad \tau \in [t+1, \min(t + T_{dn}(i) - 1, N_t)], \qquad t \in [1, N_t - 1], i \in [1, N_i] \tag{17}$$

Thermal power plants ramping has been defined in Eq. 18-20, while thermal power plants reserve provision capability has been defined in Eq. 21-24.

$$P(t,i) - P(t-1,i) \leq n(t-1,i) * V_{up}(i) * \Delta + v_{on}(t,i) * P_{min}(i), \qquad t \in [2, N_t], i \in [1, N \tag{18}$$

$$P(t,i) - P(t-1,i) \leq \left(P_{max}(i) * n(t-1,i) - P(t-1,i)\right) + v_{on}(t,i) * P_{min}(i), \qquad t \in [2, N_t], i \in [1, N_i] \tag{19}$$

$$P(t-1,i) - P(t,i) \leq n(t,i) * V_{dn}(i) * \Delta + v_{off}(t,i) * P_{min}(i), \qquad t \in [2, N_t], i \in [1, N_i] \tag{20}$$

$$r_{up}(t,i) \leq P_{max}(i) * n(t,i) - P(t,i), \qquad t \in [1, N_t], i \in [1, N_i] \tag{21}$$

$$r_{dn}(t,i) \leq P(t,i) - P_{min}(i) * n(t,i), \qquad t \in [1, N_t], i \in [1, N_i] \tag{22}$$

$$r_{up}(t,i) \leq V_{up}(i) * n(t,i) * \Delta, \qquad t \in [1, N_t], i \in [1, N_i] \tag{23}$$

$$r_{dn}(t,i) \leq V_{dn}(i) * n(t,i) * \Delta, \qquad t \in [1, N_t], i \in [1, N_i] \tag{24}$$

Hydro power plants possess energy storage capabilities in the form of water accumulation. Main hydro power plant equation is water balance equation defined as Eq. 25. Variables in Eq. 25 from left to right: usable water volume of observed time step, usable water volume of last time step, inflow, turbine flow, overflow. Eq. 26 defines upper and lower boundaries for usable water volume, Eq. 27 and 28 define the same boundaries for turbine flow and overflow, respectively.

$$V_k(i) * G_h(i) \geq V(t,i) \geq 0 \quad t \in [1, N_t], i \in [1, N_{ih}] \tag{25}$$

$$Q_{max}(i) * n_h(t,i) \geq Q(t,i) \geq Q_{min}(i) * n_h(t,i) \quad t \in [1, N_t], i \in [1, N_{ih}] \tag{26}$$

$$2 * G_h(i) * Q_{max}(i) \geq S(t,i) \geq 0 \quad t \in [1, N_t], i \in [1, N_{ih}] \tag{27}$$

Eq. 28 and 29 tackle hydro power plant power generation. Eq. 28 define linearized hydro power plant generation and eq. 29 put upper and lower boundaries on it. Eq. 30 defines existing number of hydro power plants in observed power system.

$$P_h(i) = \eta_h(i) * H(i) * Q(t,i) * g * \rho_h \quad t \in [1, N_t], i \in [1, N_{ih}] \tag{28}$$

$$P_{max\,h}(i) * n_h(t,i) \geq P_h(t,i) \geq P_{min\,h}(i) * n_h(t,i) \quad t \in [1, N_t], i \in [1, N_{ih}] \tag{29}$$

$$n_h(t,i) \leq G_h(i), \qquad t \in [1, N_t], i \in [1, N_{ih}] \tag{30}$$

Pump storage facilities have additional variable in water balance equation – pumping power defined as *Qp* in Eq. 31. Eq. 32 uses variable *Qp* for pumping power calculation, while Eq. 33 doesn't allow simultaneous pumping and generation. Reserve provision of hydro and pump storage plants has been modeled in the same manner as thermal power plants.

$$Vl(t,i) = Vl(t-1,i) * kv(i) + Q(t,i) * 3600 * \Delta - Q_p(t,i) * 3600 * \Delta + S(t,i) * 360 * \Delta - S_l(t,i), \qquad t \in [1, N_t], i = RHE \tag{31}$$

$$P_p(i) = \eta_{hp}(i) * H(i) * Q_p(t,i) * g * \rho_h \quad t \in [1, N_t], i = RHE \tag{32}$$

$$a_g(t) + a_p(t) \leq 1, \qquad t \in [1, N_t] \tag{33}$$

Demand response has been modeled as increase or decrease of demand through Eq. 34 with the condition that total energy must be conserved in chosen time period through Eq. 35. Eq. 36 and 37 are upper and lower boundaries for demand increase and decrease, respectively.

$$D(t) = D_i(t) + D_{dn}(t) - D_{up}(t) \quad t \in [1, N_t] \tag{34}$$

$$\sum_{t=1+N_{t24}*k}^{\min(N_{t24}*(k+1),N_t)} D(t) = \sum_{t=1+N_{t24}*k}^{\min(N_{t24}*(k+1),N_t)} D_i(t), \qquad k \in [0, N_t/N_{t24}] \tag{35}$$

$$D_{maxdn}(t) * N_d \geq D_{dn}(t) \geq 0 \quad t \in [1, N_t] \tag{36}$$

$$D_{maxup}(t) * N_d \geq D_{up}(t) \geq 0 \quad t \in [1, N_t] \tag{37}$$

Base battery storage system equation is energy conservation equation represented with Eq. 38, variables from left to right are: energy stored in battery storage in observed time period, energy stored in previous period and power charged/discharged from battery. Eq. 39 and 40 are upper and lower boundaries for battery storage capacity and charging/discharging power, respectively.

$$C(t) = C(t-1) * kb - ef_b * P_b(t) * \Delta \quad t \in [1, N_t] \tag{38}$$

$$C_{max} * N_b \geq C(t) \geq C_{min} * N_b \quad t \in [1, N_t] \tag{39}$$

$$P_{bmax} * N_b \geq P_b(t) \geq -P_{bmax} * N_b \quad t \in [1, N_t] \tag{40}$$

Renewable energy sources are bound just with their maximal possible generation which is directly connected with weather conditions. Eq. 41 represents wind power generation and eq. 42 photovoltaics.

$$w(t) + \Omega(t) = W(t) \tag{41}$$

$$pv(t) + \Omega_{\mathrm{pv}}(t) = PV(t) \tag{42}$$

4. RESULTS AND DISCUSSION

The analyses was conducted in three separate ways. First, we defined 8 different energy mixes with thermal and hydro power plants and added different shares of wind power plants to those systems. Wind power plants were chosen as representatives of variable renewable energy sources. Secondly, we chose one of those energy mixes and added photovoltaics (and vary their and wind power plants installed power). And finally, we added energy storage and demand response and vary their share as well.

4.1. Different energy mixes with different wind penetrations

Table 1 defines percentages of different conventional technologies used in analyses.

Table 1 Different energy mixes used in analyses

Type [%] Energy mix	Nuclear (NE)	Coal (UTE)	CCGT (PTEk)	OCGT (PTEo)	Run-of-river (PHE)	Hydro small (AHEm)	Hydro large (AHEv)	Pump storage (RHE)
A	50	35	15	0	0	0	0	0
B	26	0	26	48	0	0	0	0
C	17	52	31	0	0	0	0	0
D	9	26	35	30	0	0	0	0
E	17	26	24	0	10	12	11	0
F	17	26	18	0	9	0	0	30
G	9	17	21	0	9	26	18	0
H	0	0	9	0	23	23	16	30

Figure 1 and 2 show cost decrease and wind curtailment increase for energy mixes A-D for different wind penetrations (0-80%). Figure 3 and 4 show weekly generation scheduling for D case with 0 and 40 % wind.

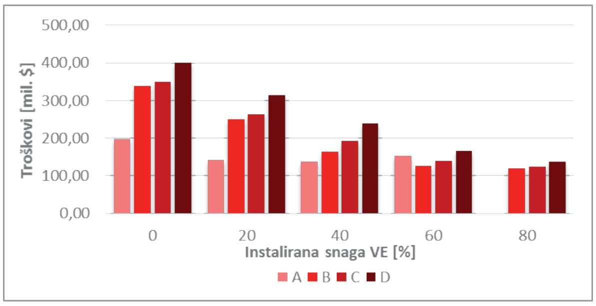


Figure 1 Total cost for A-D mixes

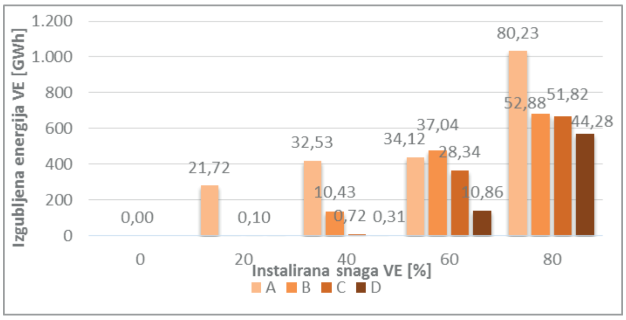


Figure 2 Wind curtailment for A-D mixes

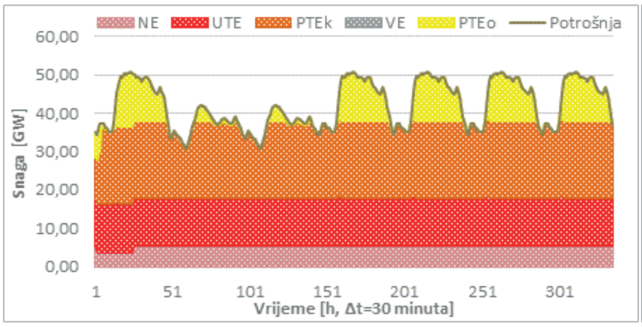


Figure 3 Generation scheduling for D mix with 0% wind

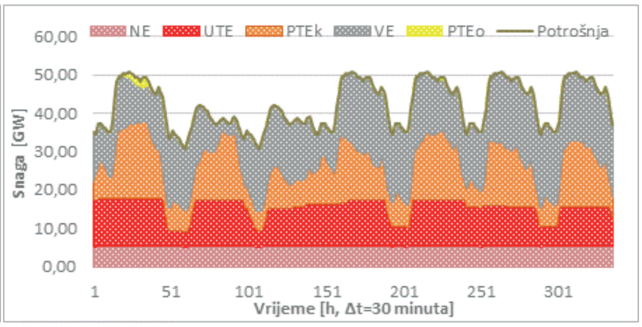


Figure 4 Generation scheduling for D mix with 40% wind

Figure 5 and 6 show cost decrease and wind curtailment increase for energy mixes E-H for different wind penetrations (0-80%). Figure 7 and 8 show weekly generation scheduling for F case with 0 and 40 % wind.

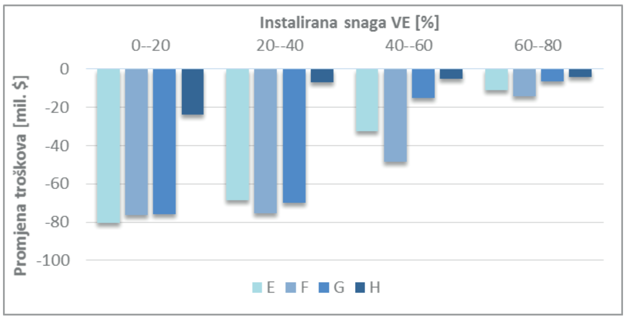


Figure 5 Total cost for E-H mixes

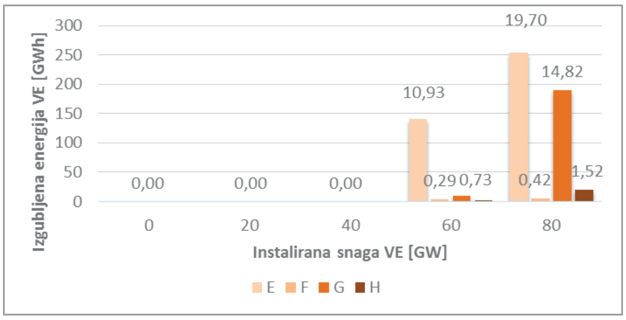


Figure 6 Wind curtailment for E-H mixes

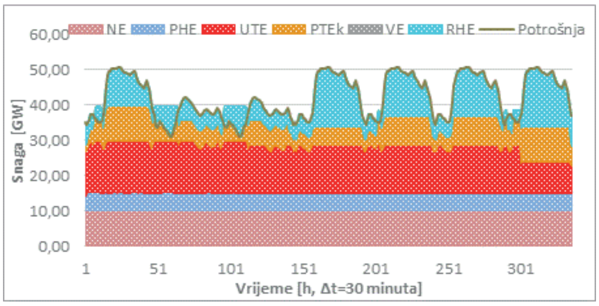


Figure 7 Generation scheduling for F mix with 0% wind

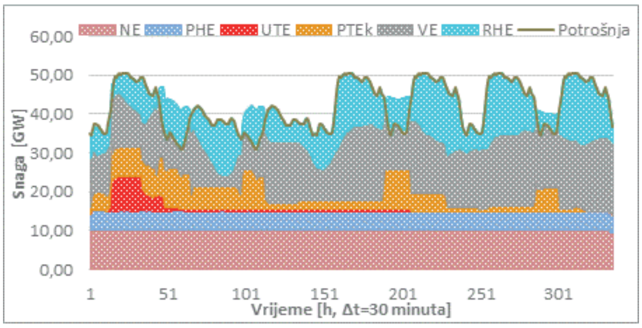


Figure 8 Generation scheduling for F mix with 40% wind

4.2. Different wind and solar power penetrations

Figures 9, 10 and 11 show cost decrease, wind and solar curtailment increase for energy mix D for different wind (0-80%) and solar penetrations (0-40%). Figures 12, 13 and 14 show weekly generation scheduling for D mix with wind penetrations (0, 40 and 80%, respectively) and 40 % solar.

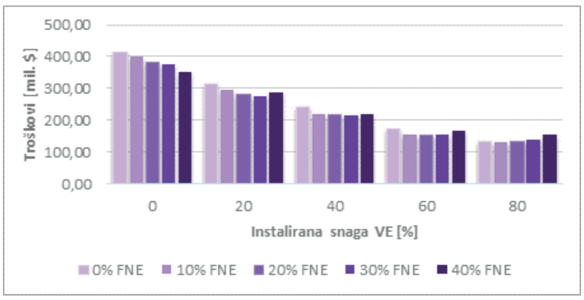


Figure 9 Total cost for mix D with different wind and solar shares

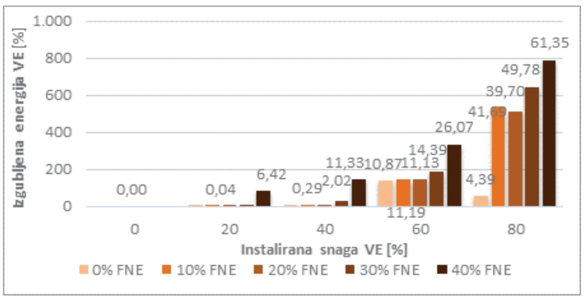
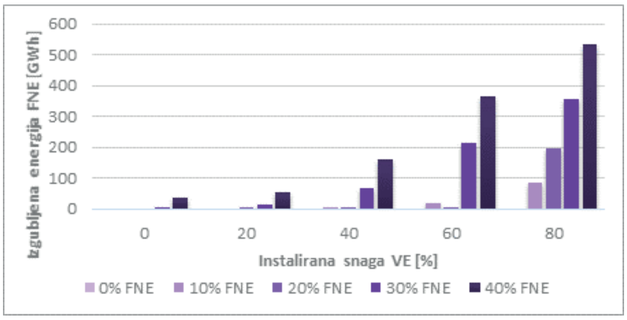


Figure 10 Wind curtailment for mix D with different wind and solar shares



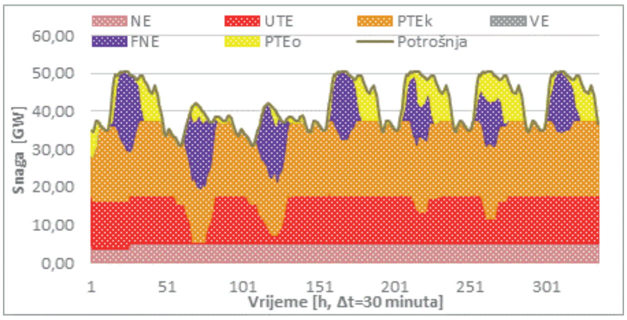
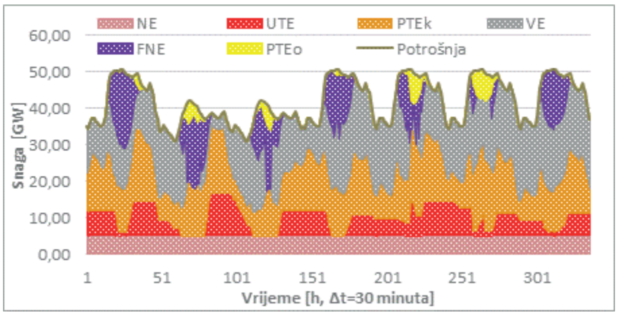


Figure 11 Solar curtailment for mix D with different wind and solar shares

Figure 12 Generation scheduling for D mix with 0% wind and 40% solar



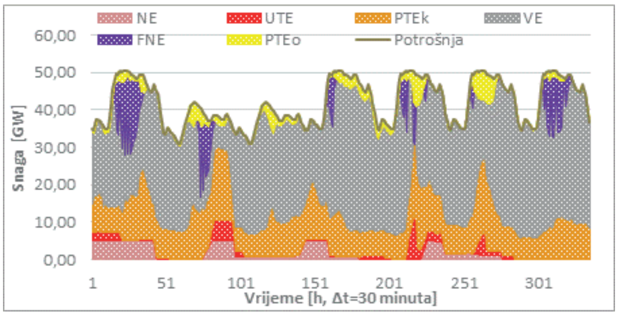
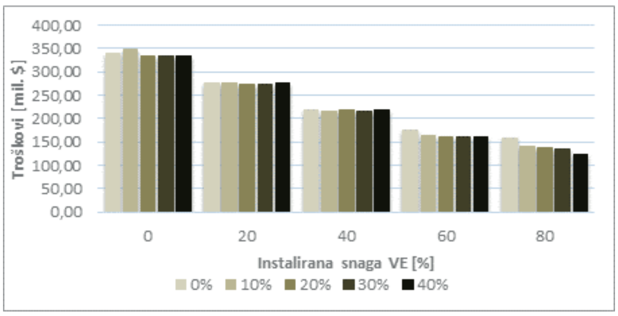


Figure 13 Generation scheduling for D mix with 40% wind and 40% solar

Figure 14 Generation scheduling for D mix with 80% wind and 40% solar

4.3. Introduction of energy storage systems and demand responses

Figures 15 and 16 show cost decrease and wind curtailment increase for energy mix B for different wind (0-80%) and adjustable demand penetrations (0-40% demand response+storage). Figures 17 and 18 show weekly generation scheduling for B mix with 80% RES penetrations (wind + solar) and 0% and 20% adjustable demand penetrations.



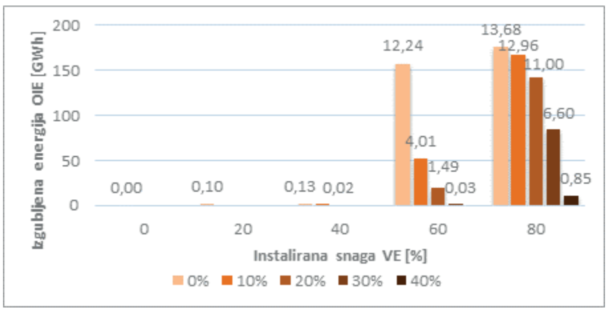


Figure 15 Total cost for mix B with different share of wind and adjustable demand (demand response+storage)

Figure 16 Wind curtailment for mix B with different share of wind and adjustable demand (demand response+storage)

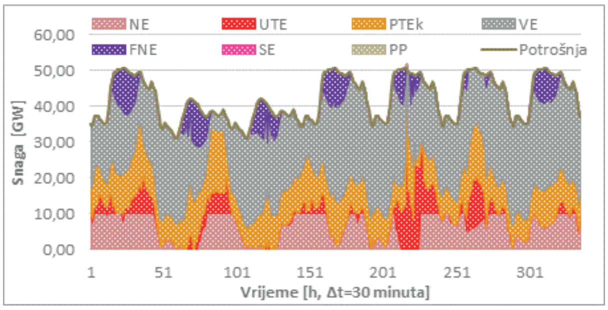


Figure 17 Generation scheduling for B mix with 80% RES (wind & solar) and 0% adjustable demand (demand response+storage)

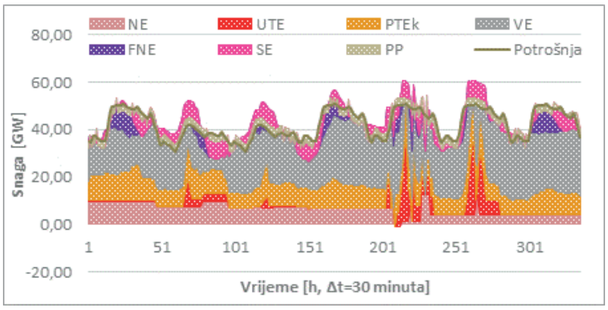


Figure 18 Generation scheduling for B mix with 80% RES (wind & solar) and 20% adjustable demand (demand response+storage)

5. CONCLUSIONS

The work presented mathematical optimization model of power systems primarily for renewable energy sources integration discussion. Model can be used as a tool to get a better insight into system's behavior under integration of different novel technologies. Model has been used with different energy mixes and penetration levels of RES technologies and the following can be concluded:

- Inflexible power plants, especially nuclear power plants, have major impact on power systems acceptance levels for renewable energy sources. More inflexible units within the system higher wind curtailment.
- Gas turbines, as the most expensive conventional power plants, are first to lose foothold when high share of RES is incorporated into system. It's cheaper for the system to curtail wind then to startup gas turbines.
- Hydro power plants drastically increase possible RES share due to their inherit flexibility.
- Pump storage facilities are the most flexible conventional units, and their proper share allows unlimited RES penetration share.
- Photovoltaics, when no wind is integrated, positively effect power systems behavior because they produce energy only during peak periods.
- High penetration of both wind and solar has negative affect on system's efficiency during periods of high generation of wind turbines and photovoltaics because large energy quantities are being curtailed.
- Energy storage and demand response have positive effect on systems with and without renewable energy sources. Without RES, they mitigate the need for peak plants, and with RES they decrease curtailed renewable power.

6. REFERENCES

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