DECARBONISING POWER SYSTEM WITH HIGH SHARE OF RENEWABLES AND OPTIONALLY WITH OR WITHOUT NUCLEAR
Slovenia Case

by

Jože DIMNIK[a,b], Peter NOVAK[a,c], and Simon MUHIČ[a,d*]

[a] Faculty of Mechanical Engineering, University of Novo Mesto, Novo mesto, Slovenia
[b] Ministry of Infrastructure, Republic of Slovenia, Ljubljana, Slovenia
[c] Energotech d.o.o., Ljubljana, Slovenia
[d] Institute for Renewable Energy and Efficient Exergy Use, Ivančna Gorica, Slovenia

Original scientific paper
https://doi.org/10.2298/TSCI201117342D

The aim of this work is to highlight challenges, if there are any, in decarbonising national power system in Republic of Slovenia. National electricity grid was hourly simulated using EnergyPlan – Advanced energy system analysis computer model in circumstances where distributed power sources capacity exceeds peak system demand. The goal was to estimate the influence of 4400 MW distributed power production to the power grid with peak demand of up to 3000 MW, respecting the fact that distributed power sources partly meet demand in summer sunlight time, however modestly meets demand in winter time. Electricity demand in summer and winter time are of the same magnitude of order. Modest system capacity for electricity storage were respected and influence to cross border transmission demand was estimated. Chalenges related to grid stability were shown and how nuclear can improve grid stability is presented.

Key words: *excessive distributed power electricity production, nuclear, cross border transmission demand, electricity production, excessive import, excessive export*

Introduction

According to Energy trilemma index [1], Slovenian national power system is ranked among top 15 worldwide in the past years, in some years even among top ten. National power system has been experiencing long lasting period of stable and secure supply of electricity. The main pillars of national power system in Republic of Slovenia consist of thermal power plants, hydro power plants, and nuclear power plant. Their share of electricity production is split to approximately one third each. Nuclear power plant operates on full power from maintenance to maintenance with modest variation of output power due to limitations related to allowed heating of the Sava river. Coal powered thermo power plants are used for meeting daily demand of electricity with some exemptions like CHP Ljubljana, which is primarily used for district heating in Ljubljana and supply of hot water and steam for industry, or gas power plant Brestanica which is used for emergency start in power shortage and for peak shaving in

* Corresponding author, e-mail: simon.muhic@inoveks.si

case hydro power plants are not able to do so due to lower river level. Hydro power plants are primarily used to operate with the flow of the river, with some hydro storage limited to approximately one hour and within that limitation hydro power plants are used for peak shaving. In addition, we considered a reversible hydropower plant with a capacity of 200 MW.

National legislation has set a target to have nearly zero-energy buildings. Reconstructed buildings are expected to have energy use around 90 kWh/m^2 per year and nearly zero-energy buildings are expected to have yearly energy use around 25 kWh/m^2 per year. Useful building surface counts around 97 million m^2 of which around 68 million m^2 is for housing. Primary use of energy for buildings is hence limited to order of magnitude 8 TWh and even lower than 3 TWh if the target 25 kWh/m^2 per year will be achieved for the majority of buildings.

National energy and climate plan (NECP) [2] have set some decarbonization related goals and in this article we would like to highlight two. To have 4400 MW of solar power plants and to decide by the year 2027 whether or not to build a nuclear power plant. Having in mind that the national power system is expected to reach capacity to cover demand in 2040 in order of magnitude 3000 MW, we might expect some challenges meeting capacity and demand in the power system and consequently, will solar power plants with their volatility and unpredictability be able to secure stability of the national power system having also in mind that neighboring power systems are expected to have surplus solar power capacity at the same period of the day as the national power system. In case recommendations are to be made we shall have in mind to primarily use energy with a high share of exergy in a sense as described in [3]. Today solar power plants and specifically photovoltaic power plants are not recognized as an essential part of the power system to provide for stability of the system. Solar power plant's capability to generate inertia required to achieve system stability is yet to be developed and tested. From the point of view of ensuring the stability of the power system, is the choice for or against nuclear power plant real or apparent or perhaps alternatives exist?

The NECP [2] has set some targets as presented in tab. 1.

Table 1. Some 2040 targets set in the NECP

Description and present data	2040	Description and present data	2040
Solar power plants	4400 MW	District heating falling 35% ref. to 2017	2.6 TWh
Wind power capacity, few MW	400 MW	Energy use in transport falling to	8 TWh
Wind production	0.5 TWh	Industry share of renewables	37%
Hydro power capacity, 1220 MW	2000 MW	Industry share of biogas	25%
Hydro power production, 4.5 TWh	6.5 TWh	Industry electricity production	7.3 TWh
Small hydro power plant	Modest rise	Industry hydrogen production	140 GWh
Biogas production	245 GWh		

Last estimation on termination use of coal is 2038. However, that might be strongly challenged by last rises in emission trading scheme (ETS) carbon market prices [4] (53.34 € on May 11th 2021). In NECP that price level is estimated in year 2040. In the last two years ETS carbon market price doubled. Figure 1 shows split between three main productions when ETS price was half the today's price and in fig. 2 the same split in production at today's ETS price. Most of the thermo production is coal. It looks like when ETS prices are high, coal production is maintained at technical minimum to be available in the case system would require additional capacity. In case ETS prices are affordable then coal production meets daily demand as shown in fig. 1.

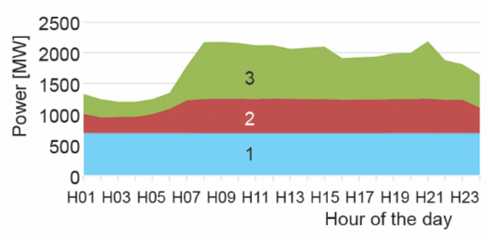

Figure 1. Production mix on May 20, 2019;
1 – nuclear, 2 – thermo, and 3 – hydro

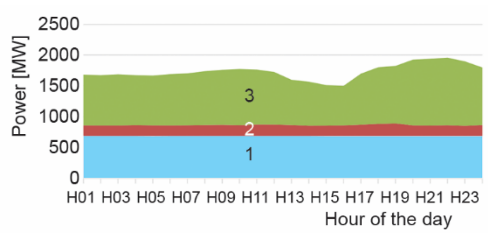

Figure 2. Production mix on May 20, 2021;
1 – nuclear, 2 – thermo, and 3 - hydro

District heating is not expected to significantly change in 2040, combined heat and power (CHP) is expected to grow to 1.6 TWh, boiler will decrease from 0.55 TWh to 0.155 TWh, heating pumps will double to 0.13 TWh and solar collectors remain modest at 8 GWh. According to NECP use of energy in 2040 in transport shall drop from 23.4 TWh to 15 TWh, in industry modest rise from 14.96 TWh to 15.27 TWh is expected and in industry CHP end use of energy will grow from 0.25 TWh to 0.63 TWh, further end use in consumer sector will be reduced from 18.7 TWh to 15 TWh. Final energy use is predicted to drop from 56.5 TWh in 2017 to 44.5 TWh in 2040. Two scenarios are feasible according to NECP: synthesized gas and nuclear and primary energy use is estimated to 65 TWh and 80 TWh, respectively. Most significant differences are reduced use of natural gas, increased use of nuclear and close to four times increased export of electricity.

Cross border interconnections exist towards Italy, Croatia, and Austria and maximum values are up to 800 MW, 1500 MW, and 950 MW, respectively. New 400 kV transmission line Cirkovce Pince will enhance the transmission network towards eastern Europe *via* Hungary. Up to 2040 further capacity has to be built in 400 kV and 220 kV network in order to meet demand related to increased renewables production. New services are to be developed as demand response, demand side management, distribution system management and energy management system, all in order to provide for stability and security of electricity supply.

National transmission system plan [5] and NECP slightly differ. In addition, national transmission system development plan in four scenarios estimates distributed sources from 1248 MW to 6250 MW in 2040. Most variation relates to solar power plants 904 MW to 5361 MW. In addition to national growth of renewables, substantial growth of renewables is expected in regions North Europe, East Europe, Balkans, Italy, Great Britain and Ireland, Turkey and Cyprus, South West Europe and Central Europe from close to 30 GW to over 120 GW, respectively in 2040. Consequently, Europe wide unused energy is estimated, which will not be able to transport outside the national grid, from up to 1 TWh in Slovenia, to over 30 TWh in Germany in 2040, should the grid remain at capacity level in 2025.

In this article, research of the national electricity system on the basis of adopted planning documents, identification of challenges and suggestion of possible solutions to mitigate these challenges with focus on ensuring the stability of the electricity system is presented. The used boundary conditions were based on the planned development of the national energy system and on the planned approaches to decarbonisation of energy systems.

Methods

National targets presented in Introduction attract attention as follows. Target for photovoltaic capacity is set to 4400 MW in 2040 and assessment to have demand at the same time in order of magnitude 3000 MW. Having in mind that distributed photovoltaics are not yet recognized as a system power plant in capacity to provide for grid stability, some challenges are expected related to grid stability on one hand and on the other hand different approaches are possible to allow higher penetration of renewables into energy system [6]. Penetration in national system has breaking even point beyond which growth of renewables is not economically justified, like in Denmark 55-57% [7]. Another Danish study [8] shown that depending on country specifics upper limit exists beyond which district heating is not optimal any more, like in Denmark 63% to 70 %.

Respecting the fact that photovoltaic will not be able to secure grid stability, some additional production capacity will have to operate in a satisfactory amount of capacity. Having that in mind two consequences are to be expected, strongly over acceptable 5% [9] of excessive energy production is expected and heavy cross border transmission towards technical limits of the existing grid is expected. Those experience-based assessments were modelled using EnergyPLAN software [10]. Expectations were confirmed by modeling, which on an annual level shows an acceptable critical excess electricity production (CEEP) below 5%, annual surplus energy in relation to annual energy consumption, on a monthly basis in July and August goes to 10%, and on an hourly basis shows unacceptable around 100% depending on the day. Percentages on a monthly and hourly basis are relative values of CEEP by power in relation to demand. EnergyPLAN was used because it enables hourly analyses of the system and it has been used for modelling energy systems with high share of renewables in following countries: Latvia [11], North Macedonia [12], Portugal [13], Croatia [14], Denmark [15], and Ireland [16].

Unfortunately, some constraints as previously described limited modelling away from exemplary as in Denmark [15, 17] approach. Namely, respecting ambitious national targets for building efficiency, share of renewables in end use energy, limits approach to handle excessive electricity production. Reducing renewables, replacing CHP with boiler, replacing boiler with electric heating are not considered in line with already accepted national targets. Some new approaches should be considered towards 4th and 5th generation of district heating [6, 18]. Transferring low temperature media over district heating grid to nearly zero-energy buildings is expected to improve energy system in two directions. First, significantly reduce energy needed for district heating and simultaneously increase share of renewables in the energy system.

Another strong limitation is decades old ban on high dam hydro power plants for which we have at least two suitable locations in capacity of several hundred MW and more than seasonal water accumulation. In the absence of this prohibition, these two hydro power plants would greatly facilitate the challenges associated to grid stability, excessive electricity production and cross border transmission. In case an independent energy system is the goal, this option should be reconsidered. Small electricity energy system can be supplied cross border, however that might influence electricity market prices. Having in mind to participate the EU 2050 target to become carbon neutral, we can count on carbon neutral synthesized hydrocarbons or H_2 which are used to temporary store excessive energy produced from renewable sources and then will be used to be converted back to electricity or used as end energy use. Latter is preferred due to higher overall efficiency. Nuclear on the other hand might be used to provide for grid stability. It is not yet clear whether or not nuclear will be recognized as in line with carbon neutral target within taxonomy. If not, financing nuclear will be challenge for itself on one hand and on the other hand only synthesized gas-powered gas turbines remain for grid stability. Having in mind social and economic acceptance of the model, nuclear power plant was used for grid stabilization over chain photovoltaic to gas, gas storage and back to electricity. Overall efficiency of the chain and modest yearly equivalent operating hours of the photovoltaic leads toward enormous capacity of photovoltaic and away from socio-economic acceptance.

Results and discussion

Having in mind already set targets for 2040, development of the grid, demand for electricity we load the EnergyPLAN with data and run the model. Hourly strings were obtained from various sources and transmission system operator for system related data and National environmental Agency for weather related data. The prediction that the coal power plant Šoštanj, producing today around one third of electricity, will not operate in 2040 was respected. Assumption has been made that weather will not change statistically significantly. All input data were measured by the source and we have checked them from a continuous flow point of view and the missing data were linearly interpolated between adjacent known data. The computational model was verified by comparing output data with the current situation.

Three warnings were generated by EnergyPLAN, for excessive electricity production, grid stability and lack of interconnection capacity.

Results show increased export of electricity in summer months when the majority of sunny days occur as shown on fig. 3. Export is correlated to sun radiation, while import strongly correlates to heat demand and outside temperature.

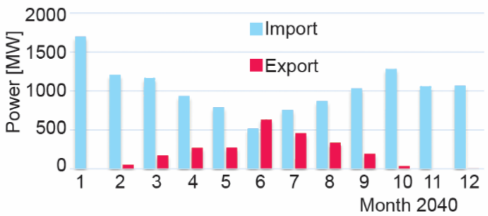

Figure 3. Prediction of imports and exports of electricity in 2040

As mentioned in [5] unused energy is estimated EU wide and we can reasonably doubt that excessive energy production during photovoltaic peak season will be economically reasonable placed on the market. Instead, conversion to carbon neutral gas or liquid energy carrier is expected, as also described in [19]. Further increased import of electricity in January is shown. We might expect that photovoltaic production is low in winter time and hydrology is low and hence production from hydro power plants is low. As already mentioned, high dam pump hydro power plants might contribute significantly to both reducing export in summer time and reducing import in winter time.

Changing central power production by adding additional nuclear power capacity to 1600 MW eliminates warning related to grid stability. EnergyPLAN estimates whether or not grid stability will be challenged according to the relationship between electricity production capacities able to participate in grid stability and capacities unable to participate in grid stability. In case the relationship is satisfactory, grid stability is not challenged, otherwise grid stability warning is generated. That capacity could be achieved by operating an existing nuclear power plant in 2040 and adding a new nuclear power plant with capacity of 1000 MW or closing existing nuclear power plant before or around 2040 and installing a new nuclear power plant in capacity of 1600 MW. Single 1100 MW nuclear block or several small or medium reactors could operate in the same capacity. From the modelling point of view last two options differ. In the case of small and medium reactors it would make sense to place them near large cities and use them also for covering heating demand. Even if they would be constructed in a way *no matter what, no influence outside the perimeter of the power plant* it is hard to believe that they would be accepted by local population. *No matter what…* technology is not commercially viable yet, but it might be in 2040 if some major constraints will be removed in time. Firstly nuclear has to be accepted within taxonomy as in line with the decarbonization target. Secondly, small and medium reactors will have to be at least EU wide if not worldwide unified in licensing and permitting. If latter is not achieved small and medium reactors lose their competitiveness. In case of one larger nuclear block, we might expect that it will be located on site of an existing nuclear power plant which is remote with respect to large domestic cities, however relatively close to over a million-population city across the border. We might expect warnings to be highlighted related to the earthquake zone. Location of the nuclear reactor strongly influences feasibility of its use for district heating. Stabilising national grid is not feasible if nuclear is not recognized as in line with carbon neutral policy or if obligatory national renewables share in end use energy is set to high.

Excessive electricity production warning is eliminated if we dedicate majority of technical capacity of cross border transmission lines to handle excessive electricity production. Majority interconnection capacities are today dedicated to support trade towards Italy and that might be affected by increasing demand for cross border capacities caused by excessive electricity production. The challenges are best seen on fig. 4 for a system that has 4400 MW of photovoltaics and has a peak power below 3000 MW.

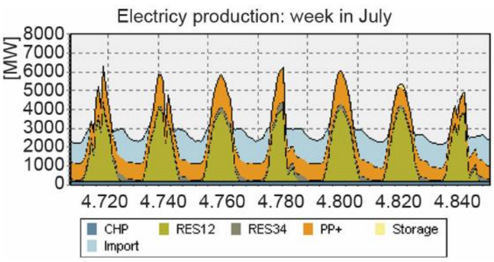

Figure 4. EnergyPLAN simulation of transmission system situation in case mitigation measures are waived [10] (*for color image see journal web site*)

In July we might expect peak solar production during solar radiation peak hours that exceeds current demand. Huge gradients of the system power are expected in the system on the daily basis as shown on fig. 4. Unless substantial capacities for electricity or shade storage are available, huge demand for cross border capacities are expected. In this phase we did not decide on the export of excess energy or conversion into hydrocarbons or hydrogen, but we were only interested in how much of this excess energy is given. The configuration of the terrain in the country does not allow us to store this amount of excess energy with hydropower plants. Short term energy storage partly solves day to day challenges, however transferring summer excessive electricity production to winter time requires substantial long term storage capacities in order to avoid economic challenges related to the fact that selling electricity during excessive offer and buying during excessive demand does not pay off.

Having in mind that it took over twenty years from beginning of the planning of the 400 kV transmission line to constructing, we cannot expect that any new transmission line will be constructed until 2040 except for the Cirkovce-Pince already in construction. Since cross border capacities have to be agreed between countries it is hard to rely on sufficient cross border capacities in 2040 dedicated for managing excessive electricity production.

Currently distributed photovoltaics is not recognized as a grid stabilisation capacity. Theoretically we can set in EnergyPLAN minimum grid stabilisation share to zero, with that we grant distributed renewables ability to provide for grid stability. We can observe that prediction of grid stability is not an issue even if we stick only with existing nuclear power plant in 2040.

But what would we have to do, to make distributed photovoltaics able to participate in grid stabilisation? By analogy with conventional large power blocks, distributed photovoltaics shall act as a single several hundred MW block, with ability to provide for stable frequency, further to change output parameters up and down from current working point. Consequently, all solar radiation available on site will not be transformed into electricity. How low or high working point would be, indicates how much more than predicted 4400 MW photovoltaics would have to be installed. If the working point would be 30% below maximum then the first approximation would be that around 500 MW additional capacity would have to be installed assuming 1500 MW distributed photovoltaics would participate in grid stabilisation. More challenging is how to achieve that distributed photovoltaics would behave like one several hundred MW block. At least following demands would have to be meet:

– Their change of output parameter would have to be synchronized. That confronts us with demand to have a centrally generated clock similar to that in global positioning systems. Precise clock and commands would have to be distributed *via* continuous connected communication system in which all distributed photovoltaics joined in a single block would be connected all the time. Assuming average distributed photovoltaics capacity is 11 kW then over 45000 distributed photovoltaics would have to be joined in action in order to form one 500 MW block. Most likely pulling every distributed source is not an option since less than 0.5 μs would be available to communicate to one source if we would like to communicate to all distributed sources within one grid frequency period. Problem can be reduced in case sufficient large floating photovoltaics on acceptable lake sides are installed. Changing output parameter in distributed sources once per grid frequency period would generate initial distributed sources inertia, essential to provide grid stability. Additional inertia could be generated by system software and distributed towards distributed sources via communication system.
– It would simplify the system if all distributed sources would be located in an area with similar solar radiation. Clouds might shade photovoltaics; hence it would not be able to maintain in desired working point. Luckily change in solar radiation, due to clouds, is relatively slow compared to changes in grid regulation and eliminating the influence of cloud shading of photovoltaics should not be too much of a challenge.
– All distributed sources grouped as one larger bloc should be connected via at least broadband internet access if not via dedicated uninterrupted communicating channel. Most likely between distributed sources and the central unit several concentrators will be installed in order to reduce mileage of dedicated lines and to avoid huge number of ports in the central unit. According to the national telecommunication regulator 84% of households already have broadband internet access [20].

In principle demands described above can be meet today, so reasons that distributed sources are not yet used to participate in grid stability are not of a technical nature. Challenge is how to convince investor to invest in capacity that will not be used most of the operating time. That is the case when working point of distributed source is not set at maximum, but lower, presumably at around 70% of maximum power according to current Sun radiation. Investment in capability of distributed sources to participate in grid stabilisation might have significant impact in socio economic acceptance of this approach even if R&D cost of the system will not be covered only by investor in distributed source. Comprehensive approach as described in [17] is recommended in order to avoid unnecessarily investments in energy system.

To resume analysis results of the national approach to decarbonization. In principle this approach is technically feasible. We have to have in mind that a significant amount of excessive energy will be exported in periods when photovoltaics peaks its production not only nationally but also in neighboring countries [5] as shown in fig. 5.

Picture shows that distributed photovoltaic sources produce electricity in correlation with sun radiation and combined with sources needed to provide for grid stability, doubles the demand in summer time, while in winter time substantial import is expected unless long time energy storage will be available.

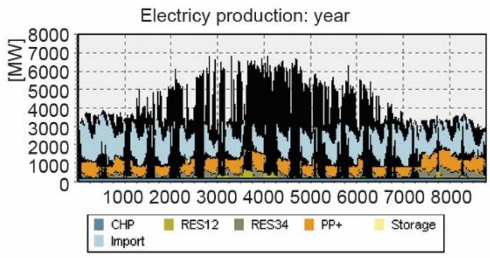

Figure 5. Excesive import in winter, and export in summer [10] (*for color image see journal web site*)

Very low prices if not negative prices are expected. On the other hand, significant import in winter time is expected, that is the period when photovoltaic is modest in production, hence very high prices are expected. It is hard to imagine that investor would willingly invest in capacity whose produced electricity is poorly paid at the time of peak production. When we reach the share of end use energy and capacity of electricity production from distributed sources compared to that in conventional block, effect on electricity market could be expected. In the electricity market prices modest or even negative electricity prices in summer time and excessive prices in winter time might be expected. Industry will most likely adjust to those changes in a way to either tend to have holidays in winter time and peak production in summer time or to move production to an environment with stable and lower prices of electricity. When the national decarbonization approach potentially affects competitiveness of the economy consideration of alternative approaches is recommended.

On first sight solution should be found to avoid excessive export of electricity in summer time and heavy demand of electricity import in winter time. In analysis we have taken into account that H_2 can be absorbed by a natural gas transmission system up to 10% of the capacity of a gas transmission system. Further transformation power to gas loses attraction because long term hydrogen storage is still challenging and conversion to gaseous or liquid hydrocarbons suffer from low overall efficiency.

The Republic of Slovenia is rich in forests. According to the national forest service 1.4 million m^3 of biomass can be used annually for energy purpose [20]. Referring to conversion factor from wood to electricity [21] up to 4.5 TWh of electricity can be produced from biomass. In addition, we gain a considerable amount of heat, depending on technology efficiency from up to 20% to up to 45%, Stirling engine to co-firing coal and biomass, respectively. Using biomass in cogeneration plant reduces the need for exporting electricity in summer time and importing expensive electricity in winter time while we simultaneously maintain the share of renewables in end use of energy. Further analysis is needed on how to optimise cogeneration biomass plant. From the socio-economic acceptance perspective, at least two options exist, according to local heat demand or according to local electricity demand. To reduce investment cost in district heating grid, heating should be limited to buildings in the vicinity of cogeneration. Or in other wordings, cogeneration should be located near heat demand. In case electricity produced in cogeneration exceeds local demand, households not connected to district heating should be stimulated to use heat pumps for heating. Unfortunately, density of habituated areas is modest and the percentage of households connected to district heating is not expected to reach 70%. Only two densely populated areas exist and the rest are rear or medium populated areas. In case local electricity capacity does not meet local heat pump demand, households using heat pumps should be stimulated to have heat storage. This approach reduces the need for storage of excessive electricity from summer to winter. In case that local electricity demand determines the capacity of the biomass cogeneration and excess heat production occurs, we have to consider local volume of near zero-energy buildings and possibility to use heat for cooling. Biomass can also play significant role in production carbon neutral gas as described in [22].

Conclusions

The research demonstrates consequences of installing photovoltaics in capacity that exceeds demand in the year 2040. As shown on fig. 4 gradients of power change in order of magnitude 3 GW within a few hours might be expected. In order to ensure grid stability at least one of two possibilities, or their combination, will have to be available. Sufficient cross border capacity towards the adjacent system capable of managing significant gradients of power change will have to be arranged or additional capacity capable of ensuring grid stability will have to be installed within the national system. Both options are expected to have comparable long-term influence on socio economic acceptance of large photovoltaic installations in the grid since technical challenges that need to be addressed are comparable.

At the time of writing this article distributed photovoltaics were not recognized as capacity capable of ensuring stability of the grid. The article suggests the way that makes distributed photovoltaics capable of participating in grid stability, however that raises challenge of socio-economic acceptance of that approach since significant additional photovoltaics and/or storage capacity would have to be installed to meet the same share of renewables target. Large reverse hydro power plants capable of yearly storage of potential energy would perfectly fit the system with excessive amount of photovoltaics, unfortunately large high dam hydro power is not publicly accepted. Also analysis of a system with a high percentage of renewable energy sources, ensuring system stability with either pumped storage hydropower plants or a nuclear power plant, shows that the use of pumped storage hydropower plants is less competitive [23].

System simulation shows excessive energy production during summer and energy lack during winter. That can be balanced by converting excessive energy to liquid or gaseous hydrocarbons during summer which can be converted back to electricity or be used as end energy during winter. That approach is affected by overall efficiency that results in additional photovoltaics to be installed to meet the same renewables share target. Should nuclear power be accepted as appropriate with European decarbonization targets, properly sized could reduce challenges related to grid stability, transfer of summer excessive energy to winter and excessive cross border capacity demand.

The national plan for 2040 has been made considering yearly energy balance. Additional effort will have to be made to consider hourly energy balance in order to avoid challenges related to grid stability, excessive energy production and excessive cross border capacity demand.

References

[1] ***, World Energy Council, World Energy Trilemma Index, London, 2020 https://www.worldenergy.org/assets/downloads/World_Energy_Trilemma_Index_2020_-_REPORT.pdf
[2] ***, Republic of Slovenia, Integrated national energy and climate plan of the Republic of Slovenia, Ljubljana, 2020, https://ec.europa.eu/energy/sites/default/files/documents/si_final_necp_main_en.pdf
[3] Novak, P., Exergy as Measure of Sustainability of Energy System, *Int. J. Earth Environ. Sci.*, *2* (2017), 2, pp. 1-19
[4] ***, Ember, Carbon Price Viewer, https://ember-climate.org/data/carbon-price-viewer/
[5] ***, ELES, Slovenian network development plan 2021-2030, Ljubljana, 2020 https://www.eles.si/Portals/EN/Document/ELES_Development_plan_2021-2030-single_page.pdf
[6] Lund, H., *et al.*, 4th Generation District Heating (4GDH). Integrating Smart Thermal Grids Into Future Sustainable Energy Systems, *Energy*, *68* (2014), Apr., pp. 1-11
[7] Muenster, M., *et al.*, The Role of District Heating in the Future Danish Energy System, *Energy*, *48* (2012), 1, pp. 47-55
[8] Lund, H., *et al.*, The Role of District Heating in Future Renewable Energy Systems, *Energy*, *35* (2010), 3, pp. 1381-1390
[9] Pfeifer, A., *et al.*, Increasing the Integration of Solar Photovoltaics in Energy Mix on the Road to Low Emissions Energy System – Economic and Environmental Implications, *Renew. Energy*, *143* (2019), Dec., pp. 1310-1317
[10] ***, Sustainable Energy Planning Research Group, EnergyPLAN Advanced Energy Systems Analysis Computer Model (Version 15), Aalborg University, Denmark, https://www.energyplan.eu/
[11] Porubova, J., Bazbauers, G., Analysis of Long-Term Plan for Energy Supply System for Lat*via* that is 100% Based on the Use of Local Energy Resources, *Environ. Clim. Technol.*, *4* (2010), 1, pp. 82-90
[12] Ćosić, B., *et al.*, A 100% Renewable Energy System in the Year 2050: The Case of Macedonia, *Energy*, *48* (2012), 1, pp. 80-87
[13] Krajačić, G., *et al.*, How to Achieve A 100% RES Electricity Supply for Portugal?, *Appl. Energy*, *88* (2011), 2, pp. 508-517
[14] Krajačić, G., *et al.*, Planning For A 100% Independent Energy System Based On Smart Energy Storage For Integration Of Renewables And CO_2 Emissions Reduction, *Appl. Therm. Eng.*, *31* (2011), 13, pp. 2073-2083
[15] Lund, H., Mathiesen, B. V., Energy System Analysis of 100% Renewable Energy Systems-the Case of Denmark in Years 2030 and 2050, *Energy*, *34* (2009), 5, pp. 524-531
[16] Connolly, D., *et al.*, The First Step Towards a 100% Renewable Energy-System for Ireland, *Appl. Energy*, *88* (2011), 2, pp. 502-507
[17] Lund, H., *Renewable Energy Systems – A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions*, 2nd ed, Academic Press, New York, USA, 2014
[18] Buffa, S., *et al.*, 5th Generation District Heating and Cooling Systems: A Review of Existing Cases in Europe, *Renew. Sustain. Energy Rev.*, *104* (2019), Apr., pp. 504-522
[19] Novak, P., Sustainable Energy System with Zero Emissions of GHG for Cities and Countries, *Energy Build.*, *98* (2015), July, pp. 27-33
[20] ***, Agency for communication networks and services of the Republic of Slovenia, eAnalyst, Data portal designed to present data on the electronic communications market in the Republic of Slovenia., https://eanalitik.akos-rs.si/en/
[21] Kofman, P. D., Units, Conversion Factors and Formulae for Wood for Energy, 2010
[22] Novak, P., The Role of Biomass for Gas Production in the Transition to a Sustainable Energy System STRESS (In Slovenian), *Rev. plin*, *2* (2018), 2, pp. 12-28
[23] Grković, V., Doder, D., Competitiveness of Power Systems with Nuclear Power Plants and with High Participation of Intermittent Renewable Energy Sources, *Thermal Science*, On-line first, https://doi.org/10.2298/TSCI210203182G, 2021

Paper submitted: November 17, 2021
Paper revised: December 7, 2021
Paper accepted: December 9, 2021