CHEMICAL ENGINEERING TRANSACTIONS
VOL. 88, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Yee Van Fan, Jiří J. Klemeš

ISBN 978-88-95608-86-0; **ISSN** 2283-9216

DOI: 10.3303/CET2188192

Energy Integration within Sectors to improve the Efficiency of Renewable Energy System within the EU

Sanja Potrč, Andreja Nemet, Lidija Čuček, Zdravko Kravanja*

University of Maribor, Faculty of Chemistry and Chemical Engineering, Smetanova ulica 17, 2000 Maribor, Slovenia
zdravko.kravanja@um.si

To achieve the goal of a carbon-neutral EU by 2050 and accelerate the transition to a sustainable energy system, synergies need to be achieved between renewable energy production, energy efficiency improvement, technology development and widespread electrification. This work presents a synthesis of sustainable renewable energy supply networks to achieve the transition to a 100 % renewable energy system in the EU by 2050, focusing on heat and power end users in various sectors to achieve more synergies between sectors and thus increase the overall efficiency of the energy system. The generation and supply of renewable electricity, heat, first, second and third generation biofuel, hydrogen and bioproducts from different renewable energy sources are considered together with storage technologies. A dynamic mixed-integer linear programming model is formulated with the maximization of the composite criterion Sustainability Net Present Value as the objective, optimizing all sustainability pillars simultaneously. The results show the impact of electrifying the residential sector, services and transport sector to accelerate the transition to a sustainable energy future. Heat pumps powered by renewable electricity seems to be a key technology for meeting heating demand in residential and service sector, accounting for 55 % and 61 % of final consumption. The results also reveal the role of biomass cogeneration systems, whose heat recovery could meet 33 % of the heat demand from renewable energy sources in the residential sector and 28 % in the services. The share of electricity in final energy consumption in the transport sector is projected to reach 52 %. The residential, services and transport sectors together are expected to almost double the current electricity demand by 2050.

1. Introduction

The increasing global demand for energy and the associated impact on the environment and humankind require an accelerated transformation of the energy system and further developments towards more efficient energy production, supply and use. Reducing primary energy consumption and dependence on energy imports is of increasing importance for improving of the energy supply security of European Union (European Commission, 2018). To accelerate the transition to a sustainable energy future, synergies between renewable energy generation, energy savings and improvements in technological efficiency need to be exploited (Lu et al., 2020). The share of energy from renewable energy sources in the EU remains low, especially in the transport and heating and cooling sectors, where it accounts for 8.9 % and 22.1 % (Eurostat, 2020). There is also a large untapped potential for energy efficiency improvements, especially in buildings, with improving linkages between electricity and heating systems and the use of waste heat (European Commission, 2016). A combination of renewable energy deployment, energy efficiency improvements, use of storage technologies and electrification of end-uses is key to achieving the goal of a carbon-neutral EU by 2050 (Zhao and You, 2020), which is in line with global climate action to achieve the below 2 °C target in the Paris Agreement. Together with the reduction of greenhouse gas emissions and air pollution, the energy transition would enable faster economic growth, the creation of additional jobs and, ultimately, an improvement in overall welfare.
The transition to a 100 % renewable energy (RE) system has been studied extensively over the last decade for countries (Hansen et al., 2019b), regions (Potrč et al., 2020a), continents (Child et al., 2019) and globally (Ram et al., 2017), with the importance of applying a cross-sectoral approach to synthesizing the RE system increasing significantly in recent years (Hansen et al., 2019a). The coupling of different sectors enables to obtain more synergies between sectors (Dominković et al., 2016) and also to integrate a high level of intermittent renewable

Paper Received: 31 May 2021; Revised: 9 September 2021; Accepted: 9 October 2021
Please cite this article as: Potrč S., Nemet A., Čuček L., Kravanja Z., 2021, Energy Integration within Sectors to improve the Efficiency of Renewable Energy System within the EU, Chemical Engineering Transactions, 88, 1153-1158 DOI:10.3303/CET2188192

energy sources (RES) (Lund et al., 2015), which allows a better management of variable RE generation (Dorotić et al., 2019). The aim of this work is to synthesize renewable energy supply networks to achieve an optimal transition to a renewable energy system within the European Union (EU-27) by 2050, focusing on the synergistic exploitation between heat and power supply network to increase the efficiency of the entire energy system. It has already been shown that the optimization of renewable energy supply networks at larger geographical scales explores more synergies (Potrč et al., 2021), so the novelty of this study is to exploit positive synergistic effects between heat and power supply network systems by considering co-generation and heat pump options. Moreover, by separating the energy demand into heat and power demand, a more detailed technology selection and optimization could be achieved.

2. Methodology

The methodology for the synthesis of renewable energy supply networks, considering heat and power demand and the technologies linking the supply systems of both sectors, was based on the four-layer supply network superstructure, first proposed by Čuček et al. (2010). EU was divided into 47 zones according to regional specifications (RES availability) and energy demand, with each Member State represented by at least one zone (Potrč et al., 2020b). The first layer considers the availability of different RES in each zone, and the second layer includes different pre-treatment technologies (biomass pre-treatment, algae oil extraction, etc.), storage facilities, and generation of electricity from intermittent sources and geothermal energy. The third layer includes other electricity and heat generation technologies (those requiring feedstock pre-treatment) and biorefineries, while the fourth layer includes the demand for electricity, heat and biofuels from RES in different sectors, including logistics within and between the different layers.

In this study, the model was extended by defining heat and electricity demand separately for all sectors, considering the cogeneration option, heat pumps, and the possibility of converting currently operating coal-fired power plants into biomass cogeneration plants, as well as the use of biowaste in waste-to-energy plants. Therefore, the superstructure contains all options as follows. Technologies considered for electricity generation are solar photovoltaic (PV), wind farms and geothermal power plants, while for renewable heat generation biomass boilers, geothermal systems and heat pumps using electricity generated from RES are taken into account, together with combined heat and power (CHP) plants using biomass as feedstock and waste-to-energy plants using the biowaste fraction of municipal solid waste as feedstock. The superstructure includes the possibility of converting currently operating coal-fired power plants into biomass cogeneration plants. However, cogeneration is reasonable only when heat can be utilized on the spot. For this purpose, an overview of existing thermal power plants has been made to identify those that are close enough to the demand sites to be used for district heating. The excess electricity and heat generated could be stored using pumped hydro storage (PHS) and sensible thermal energy storage (TES). For the production of diesel and gasoline substitutes (biodiesel, FT-diesel, bioethanol and “green” gasoline) and hydrogen, the following technologies are considered: i) gasification and further both, catalytic synthesis or syngas fermentation, ii) gasification and lignocellulosic hydrogen generation, iii) FT-synthesis and iv) biodiesel production from algae oil and waste cooking oil (Martin and Grossmann, 2012).

The optimization of renewable electricity, heat and fuel production and supply by 2050 was carried out using a mixed-integer linear programming (MILP) model, where the variable availability of wind and solar, heat and electricity demand were modeled on an hourly basis, while monthly periods were used for biomass and waste availability and biofuel production. In order to reduce the computational time, four periods per day and two periods per week are used for electricity and heat generation and demand and intermittent RES availability.

The model includes data on RES availability for each zone and time period, area of zones, investment costs, operating and maintenance costs for each technology, transportation costs, conversion factors, eco-cost coefficients for raw materials, technologies, transportation, energy and products, average salaries in each country for construction and operation workers, and demand for renewable heat, electricity and biofuels in each sector over the years. The constraints are the minimum and maximum capacities of technologies, the maximum allowable distances for transporting raw materials and energy, and the maximum emissions released to achieve a carbon-neutral target by 2050.

A dynamic mixed-integer linear programming model was formulated with maximization of the composite criterion Sustainability Net Present Value (Zore et al., 2018) as the objective, where all sustainability pillars are optimized simultaneously, as described in Eq(1).

$$NPV^{\text{Sustainability}} = NPV^{\text{Economic}} + NPV^{\text{Environmental}} + NPV^{\text{Social}} =$$

$$\sum_{t=0}^{T} \frac{FC_{t,\text{economic}}}{(1+r_{\text{d}})^{t}} + \sum_{t=1}^{T} \frac{EB_t - EC_t}{(1+r_{\text{d}})^{t}} + \sum_{t=1}^{T} \frac{SS_t + SU_t - SC_t}{(1+r_{\text{d}})^{t}} \quad (1)$$

The economic net present value (NPV^{Economic}) is the sum of the discounted annual net cash flows at the discount rate r_{d} over the years (t = 1,…,T). The environmental net present value ($NPV^{\text{Environmental}}$) is calculated as the difference between environmental benefits (EB_{t}) and environmental costs (EC_{t}), taking into account the unburdening and burdening effects of raw materials, technologies, transport, products and energy in year *t* using eco-cost coefficients. The social net present value (NPV^{Social}) is the sum of the social unburdening effect (SU_{t}) due to the creation of additional jobs and the social security contributions paid by employers and employees (SS_t), reduced by the social costs (SC_t).

For the gradual transition to a renewable energy system over the next 30 y the following assumptions were considered: i) the expected reduction in technology costs according to (IRENA, 2016), and ii) energy efficiency improvements according to the energy efficiency scenario in Energy Roadmap 2050 (European Union, 2012), which foresees a 41 % reduction in energy demand compared to the 2005 peak, implying energy savings of 0.8 % per year from 2020 to 2050.

The model for the synthesis of renewable energy system separately considering heat and power demand consists of about 2.6 M single equations, 102 M single variables, and 45,000 discrete variables and is formulated in the modelling system GAMS. The solutions are obtained using the solver Gurobi after 72 h of solving time on the HPC server DL580 G9 CTO (4 processors – 32 core, Intel® Xeon® CPU E5-4627 v2 @ 3.30 GHz, 768 GB RAM).

3. Results and discussion

In order to achieve the transition from the current energy system to a renewable one in the EU-27 by 2050, the following strategy is explored: i) in 2030, 50 % of electricity and heat demand should be satisfied by RES, while in the transport sector a 30 % share of renewable energy should be achieved; ii) by 2040, a 75 % share of renewable electricity and heat, and a 65 % share of RES in the transport sector should be achieved; and iii) a complete transition to RES in all sectors should be achieved by 2050. The current share of RES in each sector has been considered and the optimization focuses on the demand difference in each sector in each year between the targeted demand and the current share of renewable energy generated by existing technologies, so that the results represent the quantities of RE that need to be produced in each sector after 2020.

Figure 1 represents renewable electricity and heat consumption in the residential sector according to the technology used for generation. By 2030, the additional renewable electricity is expected to be generated mainly by wind turbines, which will provide 58,590 GWh/y of renewable electricity, followed by biomass CHP, solar PV and geothermal power plants, which together will contribute 60,705 GWh/y of renewable electricity. 20,441 GWh/y of electricity can be generated by biomass cogeneration plants, where the cogeneration plants are only those that were converted from currently operating coal-fired thermal power plants (TPPs). This was typically selected in Poland and Germany, as the investment costs are lower compared to building additional CHP plants. The non-converted TPPs are assumed to be shut down. Moreover, the optimization shows that all selected thermal power plants should be converted into biomass CHP by 2030 to reach the set targets. The generation of electricity and heat using TPP to CHP will remain constant from 2030 to 2050. This also goes hand-in-hand with the climate action of phasing out coal by 2030, leading to a significant reduction in emissions. By 2040, wind farms should remain the driving force for electricity generation from RES as they are expected to generate 137,296 GWh/y of electricity for the residential sector. In addition, solar PV, biomass CHP and geothermal power plants are expected to generate 99,234 GWh/y, 51,150 GWh/y and 39,088 GWh/y electricity, respectively. Solar PVs are expected to overtake wind turbines in electricity generation from RES by 2050, providing 40.5 % of electricity demand in the residential sector, while wind turbines are expected to contribute 29.4 %, biomass CHP 20.8 % (4 % from thermal power plants converted into biomass CHP and 16.8 % from additional CHP plants) and geothermal power plants 9.3 %.

Figure 1b shows the consumption of heat generated by different technologies in the residential sector until 2050. It can be seen that most of the demand for renewable heat in the residential sector by 2030 is expected to be met by heat pumps, which can generate 390,832 GWh/y of heat, representing 69 % of the additional renewable heat generated between 2020 and 2030.

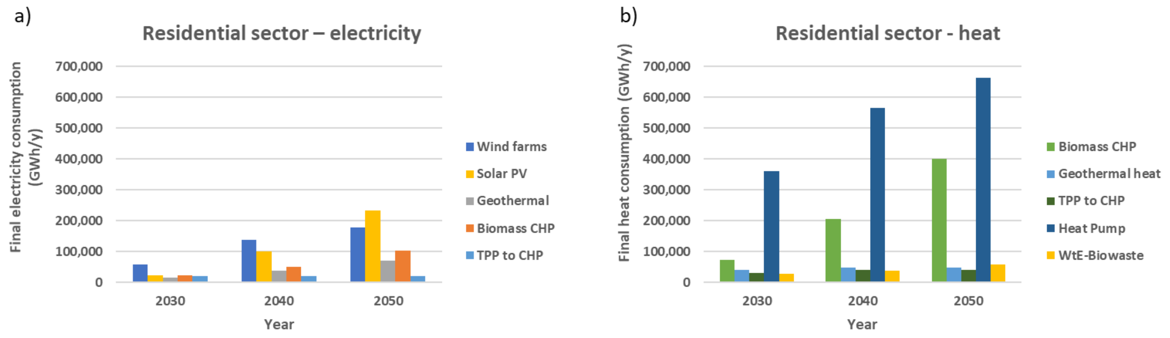

Figure 1: Final consumption of a) renewable electricity and b) renewable heat generated by different technologies to achieve the transition to 100 % renewable energy in the residential sector by 2050

Smaller amounts of heat are expected to be provided by biomass CHP and geothermal heat, 19 % (13 % of newly built CHP and 6 % by thermal power plants converted into biomass CHP) and 7 % respectively. It is also expected that the biowaste fraction of municipal solid waste will be used to generate about 5 % of the renewable heat demand, with this share remaining constant over the years. The amount of heat generated by heat pumps and biomass CHP will continue to increase until 2050. Heat pumps are expected to meet 55 % and biomass CHP 33 % of the heat demand in the residential sector. Electricity demand in the residential sector is expected to increase by an additional 78,166 GWh/y by 2030, 123,606 GWh/y by 2040, and 135,779 GWh/y by 2050, due to electricity consumption by heat pumps, enabling utilization of low potential heat. The increased electricity consumption is expected even though energy efficiency improvements of buildings have been considered in the optimisation. Most of the additional electricity needed to satisfy heat demand is expected to be generated by biomass CHP, followed by solar PV and wind farms. In the residential sector, the heat demand is about twice as high as the electricity demand, while the heat and electricity demand in the service sector is very similar, as shown in Figure 2.

The renewable electricity demand in the service sector is expected to be mainly satisfied through the use of solar PV and wind turbines by 2050, which are expected to meet 79 % of the renewable electricity demand. Biomass CHP, together with the conversion of TPP to CHP, will contribute another 14 % of electricity demand, and the remaining 7 % will be met by geothermal power plant. The share of solar photovoltaics in both sectors, residential and services, is expected to increase in the last years, especially due to the energy efficiency improvements of solar panels and the reduction of investment costs over the years.

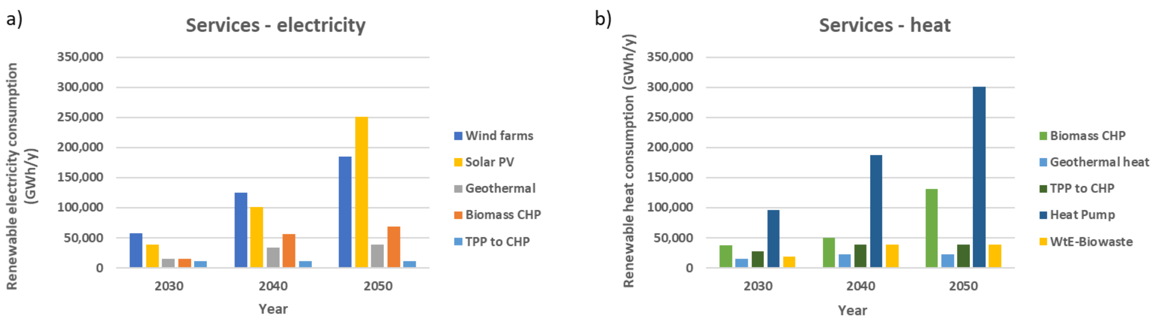

Figure 2: Final consumption of a) renewable electricity and b) renewable heat generated by different technologies to achieve the transition to 100 % renewable energy in the service sector by 2050

In terms of the heat demand from RES in services, heat pumps are expected to generate 61 % of the renewable heat required by 2050, and biomass CHP additional 28 %, of which 6 % can be generated by converting thermal power plants into biomass CHP. The remaining 11 % of demand is expected to be satisfied by geothermal heat and biowaste. Electricity consumption by heat pumps to meet service sector heating demand is projected to increase by 31,953 GWh/y by 2030, and 58,793 GWh/y by 2040, and electricity demand by heat pumps for service sector heating is projected to be 73,563 GWh/y in 2050.

The next sector that was investigated is the road transport sector, where the share of renewable energy is still very low and therefore lags behind in the transition to a renewable energy future. Figure 3 shows the consumption of different biofuels and electricity in the road transport sector until 2050. By 2030, most of the renewable energy is already expected to be achieved through electricity, which requires the generation of an additional 471,546 GWh/y (40,545 ktoe/y) of electricity from RES, followed by fossil diesel substitutes, for which only the consumption of biodiesel (27,194 ktoe/y) is proposed by 2030, the production of FT-diesel was not selected. The consumption of bioethanol and hydrogen is projected to be 11,683 ktoe/y and 13,971 ktoe/y, respectively. The share of hydrogen is not expected to change significantly by 2050 (16,369 ktoe/y), while the share of bioethanol and green gasoline in final consumption is expected to rise to 27,271 ktoe/y. On the other hand, the consumption of electricity as well as biodiesel and FT-diesel is expected to increase steadily until 2050. In the final year, 1,571,810 GWh/y (135,151 ktoe/y) of electricity will be needed to achieve the transition in the transport sector, representing 52 % of final consumption. Biodiesel and FT-diesel are expected to satisfy 32 % of demand, with biodiesel preferred over FT-diesel (68,048 ktoe/y and 17,745 ktoe/y, respectively).

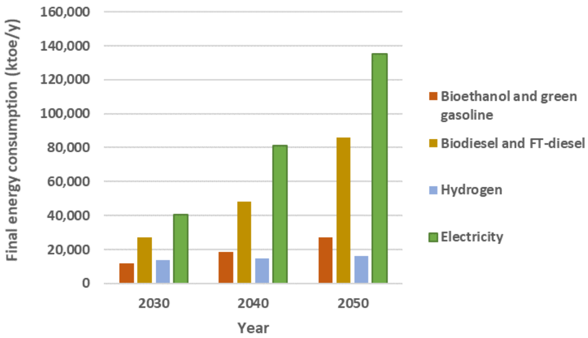

Figure 3: Final energy consumption by source to achieve the transition to 100 % renewable energy in road transport by 2050

From the results it could be observed that electrification of transport and the use of low potential heat via heat pumps in buildings are key to the transition to a renewable energy system. The share of electricity in the end-use sectors studied is expected to almost double by 2050, due to the additional electricity consumption of 1,781,152 GWh/y by heat pumps installed in the residential sector and services, and for the electrification of the transport sector, despite energy efficiency improvements in buildings.

4. Conclusions

This paper presents the synthesis of renewable energy supply networks to achieve the gradual transition to a renewable energy system with the goal to achieve a carbon-neutral European Union by 2050. Emphasis has been placed on satisfying both heat and power demand, linked via heat pump and cogeneration, to achieve more positive synergies between energy sectors and in this way increase the efficiency of the entire energy system. A dynamic multi-period mixed-integer linear programming model was developed, including different renewable energy sources and technologies for generation of renewable heat, electricity and biofuels to meet the demand for renewable energy in the residential sector, services and transport sector. The optimization was performed using the Sustainability Net Present value as the objective, optimizing all the three pillars of sustainability simultaneously.

The most promising solution to meet renewable heat demand in the EU is the utilization of heat pumps, which are expected to meet 55 % of the renewable heat demand in the residential sector and 61 % in the service sector. The additional utilization of electricity in both sectors will increase the demand for renewable electricity by 209,342 GWh/y by 2050, despite energy efficiency improvements in buildings. It is also very important to include biomass CHP systems in order to improve the efficiency of the energy system. The share of biomass CHP is expected to increase over the years, covering 33 % of the heat demand in the residential sector and 28 % in the services in 2050. The model also includes the possibility of converting currently operating coal-fired power plants into biomass cogeneration plants; in this way, a 6 % increase in share of renewable energy is expected to be covered. The remaining demand for heat is expected to be met by geothermal energy and the biowaste fraction of municipal solid waste using waste-to-energy plants. In the transport sector, the electricity demand will increase to 1,571,810 GWh/y by 2050, satisfying 52 % of the transport sector's demand. Regarding electricity demand, wind turbines have proven to be the most effective technology in the early years, while solar PV is expected to overtake wind turbines by 2050 due to energy efficiency improvements and expected cost reductions. However, in order to meet almost double demand for electricity, it is necessary to facilitate the integration of intermittent energy sources through the use of storage technologies.

The industrial sector has not been investigated in this study due to the complexity of the system, which requires a more detailed analysis, and will therefore be included in future research, together with the detailed study on the reduction of greenhouse gas emissions in each sector in order to achieve the goal of a carbon-neutral EU by 2050.

Acknowledgements

Financial support from the Slovenian Research Agency (PhD research fellowship contract No. 1000-19-0552, research core funding No. P2-0032 and P2-0412, and projects No. J7-1816 and N2-0138) is gratefully acknowledged.

References

Child, M., Kemfert, C., Bogdanov, D., Breyer, C., 2019, Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe, Renewable energy, 139, 80-101.

Čuček, L., Lam, H.L., Klemeš, J.J., Varbanov, P., Kravanja, Z., 2010, Synthesis of regional networks for the supply of energy and bioproducts, Clean Technologies and Environmental Policy, 12(6), 635-645.

Dominković, D.F., Bačeković, I., Ćosić, B., Krajačić, G., Pukšec, T., Duić, N., Markovska, N., 2016, Zero carbon energy system of South East Europe in 2050, Applied energy, 184, 1517-1528.

Dorotić, H., Doračić, B., Dobravec, V., Pukšec, T., Krajačić, G., Duić, N., 2019, Integration of transport and energy sectors in island communities with 100% intermittent renewable energy sources, Renewable and Sustainable Energy Reviews, 99, 109-124.

European Commission, 2016, An EU strategy on heating and cooling, <ec.europa.eu/energy/sites/ener/files/documents/1_EN_ACT_part1_v14.pdf> accessed 22.06.2021.

European Commission, 2018, Directive (EU) 2018/2002 of the European Parliament and of the Council of 11 December 2018 amending Directive 2012/27/EU on energy efficiency, <eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.328.01.0210.01.ENG> accessed 14.06.2021.

European Union, 2012, Energy roadmap 2050, <ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf> accessed 28.06.2021.

Eurostat, 2020, Renewable energy statistics, <ec.europa.eu/eurostat/statistics-<explained/index.php/Renewable_energy_statistics> accessed 10.06.2021.

Hansen, K., Breyer, C., Lund, H., 2019a, Status and perspectives on 100% renewable energy systems, Energy, 175, 471-480.

Hansen, K., Mathiesen, B.V., Skov, I.R., 2019b, Full energy system transition towards 100% renewable energy in Germany in 2050, Renewable and Sustainable Energy Reviews 102, 1-13.

Lu, Y., Khan, Z.A., Alvarez-Alvarado, M.S., Zhang, Y., Huang, Z., Imran, M., 2020, A critical review of sustainable energy policies for the promotion of renewable energy sources, Sustainability, 12(12), 5078.

Lund, P.D., Lindgren, J., Mikkola, J., Salpakari, J., 2015, Review of energy system flexibility measures to enable high levels of variable renewable electricity, Renewable and sustainable energy reviews, 45, 785-807.

Martin, M., Grossmann, I.E., 2012, Simultaneous optimization and heat integration for biodiesel production from cooking oil and algae, Industrial & engineering chemistry research, 51(23), 7998-8014.

Potrč, S., Čuček, L., Martin, M., Kravanja, Z., 2020a, Synthesis of European Union Biorefinery Supply Networks Considering Sustainability Objectives, Processes, 8(12), 1588.

Potrč, S., Čuček, L., Martin, M., Kravanja, Z., 2021, Sustainable renewable energy supply networks optimization–The gradual transition to a renewable energy system within the European Union by 2050, Renewable and Sustainable Energy Reviews, 146, 111186.

Potrč, S., Čuček, L., Zore, Ž., Kravanja, Z., 2020b, Synthesis of Large-Scale Supply Networks for Complete Long-term Transition from Fossil to Renewable-based Production of Energy and Bioproducts, Chemical Engineering Transactions, 81, 1039-1044.

Ram, M., Bogdanov, D., Aghahosseini, A., Oyewo, S., Gulagi, A., Child, M., Fell, H.-J., Breyer, C., 2017, Global energy system based on 100% renewable energy—power sector, Lappeenranta University of Technology and Energy Watch Group: Lappeenranta, Finland.

IRENA, 2016, The Power to Change: Solar and Wind Cost Reduction Potential to 2025, <www.irena.org/publications/2016/Jun/The-Power-to-Change-Solar-and-Wind-Cost-Reduction-Potential-to-2025> accessed 20.06.2021.

Zhao, N., You, F., 2020, Can renewable generation, energy storage and energy efficient technologies enable carbon neutral energy transition?, Applied Energy, 279, 115889.

Zore, Ž., Čuček, L., Širovnik, D., Pintarič, Z.N., Kravanja, Z., 2018, Maximizing the sustainability net present value of renewable energy supply networks, Chemical Engineering Research and Design, 131, 245-265.