CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

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

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081174

Synthesis of Large-Scale Supply Networks for Complete Long-term Transition from Fossil to Renewable-based Production of Energy and Bioproducts

Sanja Potrč[a], Lidija Čuček[a], Žan Zore[b], Zdravko Kravanja[a,*]

[a]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
[b]Frutarom Etol d.o.o., Škofja vas 39, 3211 Škofja vas, Slovenia
zdravko.kravanja@um.si

This contribution presents the synthesis of sustainable larger-scale supply networks to produce alternative energy and bioproducts across an entire system's lifetime. In particular, production of food, first, second and third generation of biofuels, hydrogen, and renewable electricity are considered. Corn and wheat grain are used for production of food; corn stover, wheat straw, miscanthus, forest residue, algae oil and waste cooking oil are biomass and waste sources for the manufacture of bioproducts; and solar, wind and geothermal sources for electricity production. The objective of supply network synthesis is the maximization of Sustainability Net Present Value, which is a sustainability metric composed of economic, environmental and social net present values. The dynamic mixed-integer linear programming problem is formulated as a multi-period model where i) monthly time periods are used for the manufacture of biomass and bioproducts, while ii) daily, hourly and monthly periods are used for the production of electricity. A case study of EU-27 is considered and gradual energy transition from the current energy supply to 100 % renewable-based production of fuels and electricity over a time horizon of 40 y is investigated. The results of this study indicate that long-term transition from fossil to renewable-based generation of electricity, fuels and bioproducts is possible to a large extent. The results suggest an optimal selection of types, locations and dynamics of technology installations across the EU in order to achieve energy transition in the transport and electricity sectors.

1. Introduction

The transition from fossil to renewable based energy can mitigate global climate change and provide environmental benefits by providing reductions of greenhouse gas (GHG) emissions and air pollution. Transport, industry, buildings and the power sector are key sectors in the transition toward a sustainable energy future (IRENA, 2018). At the EU level, the current share of renewable energy in these sectors still remains low, especially in the transport sector, where only around 8.3 % share of renewables was achieved by the end of 2018 (Eurostat, 2020).

Renewable energy sources (RES) will play a vital role in the long-term fossil-based GHG emission abatement of the European Union, especially the use of biomass for the production of biofuels and deployment of wind power and solar photovoltaics in electricity generation (Banja et al., 2019). On the other hand, there are also certain shortcomings in the utilization of biomass and other RES, such as: i) the discontinuity of energy production because of seasonality and local availability of sources (Owusu and Asumadu-Sarkodie, 2016), ii) competitiveness with the food supply chain that may cause an increase of food prices when producing the first generation of biofuels (Ghosh et al., 2019), and iii) additional cultivation area for energy purposes can lead to biodiversity loss (Elshout et al., 2019).

It is important that resources are allocated as optimally as possible from a sustainability point of view; they must be environmentally friendly, have socially favourable impacts and reflect good economic efficiency. To the best of the authors' knowledge, no research has yet been performed on the complete, gradual, long-term transition from fossil to renewable-based production of fuels and electricity on a large, almost continental scale, which also takes into account the food supply and considers sustainability as an objective.

Paper Received: 16/05/2020; Revised: 11/06/2020; Accepted: 15/06/2020
Please cite this article as: Potrč S., Čuček L., Zore Ž., Kravanja Z., 2020, 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 DOI:10.3303/CET2081174

In this study, large-scale bioproduct and renewable energy supply networks are synthesized, with the objective of maximizing Sustainability Net Present Value, NPVSustainability (Zore et al., 2018), in order to evaluate eligibility of investments over the entire system's lifetime. Production of food, biofuels, hydrogen, and renewable electricity is considered in a case study of the EU-27 to evaluate options for complete gradual energy transition over the next 40 y (by 2060) from fossil-based sources.

2. Approach for the synthesis of sustainable renewable supply networks

Methodology for sustainable synthesis of optimally integrated renewable supply networks for the production of food, first, second and third generations of biofuels, hydrogen, renewable electricity and by-products is demonstrated in a case study of the EU-27. First, supply networks are described, and further applied methodology for the synthesis is presented.

2.1 Description of sustainable supply networks

For synthesizing biorefinery and renewable electricity supply networks, a four-layer (L1-L4) superstructure was used (Čuček et al., 2010), containing sets of potential locations of harvesting sites (L1), intermediate storage, pretreatment facilities (drying, oil extraction, pre-processing) and electricity production plants (L2), biorefineries (L3) and end users (L4), including logistics between and within layers. Several renewable energy sources are considered, such as wind, solar and geothermal energy for electricity generation and wheat, wheat straw, corn grain and stover, forest residue, miscanthus, algae and cooking oil for the production of biofuels. Corn grain and wheat are also feedstocks for food supply. For conversion of RES into biofuels and other bioproducts, different technologies are considered: i) the dry grind process, ii) gasification and lignocellulosic hydrogen production, iii) gasification and syngas fermentation, iv) gasification and catalytic synthesis of biomass, v) gasification and Fischer Tropsch (FT) synthesis and vi) production of biodiesel from algal oil and waste cooking oil using methanol or ethanol as catalysts (Martín and Grossmann, 2013); and for electricity production, i) wind turbines, ii) solar photovoltaics (PV) and iii) geothermal power plants are taken into account. Using these technologies, bioethanol and green gasoline can be produced as substitutes for gasoline; biodiesel and FT-diesel as substitutes for fossil-based diesel; and hydrogen and renewable electricity are also produced.

2.2 Methodology

Sustainable supply network synthesis is based on a mixed-integer linear programming (MILP) model, where for non-linear investment terms, piecewise linear approximation is performed. The approach defines a multi-period model, where monthly, weekly and hourly time periods are considered for intermittent sources (wind, solar and geothermal energy) and electricity demands (Čuček et al., 2016), and monthly periods are considered for biomass and bioproducts. Because of large computational times, the number of periods for electricity generation and demand has been reduced to two periods per week and four periods per day. Additionally, 40 y periods are included to evaluate a gradual long-term transition from fossil to renewable-based energy within the EU. The total area of each zone, the gross and net wages in each country, the demand for food, biofuels and electricity at each location, the hectare yields of all considered raw materials in each zone and other parameters are inserted into the GAMS modelling interface in a data-independent form, taking into account dynamic changes along the supply network.

In order to keep the model solvable, various model size reduction techniques were used (Lam et al., 2011), such as: i) reducing the connectivity in a supply network by limiting the distances for distribution of feedstocks, waste materials, products and energy, and ii) eliminating variables and constraints with zero-flows.

The optimization was performed using $NPV^{Sustainability}$ as an objective, as described by Eq(1):

$$NPV^{\text{Sustainability}} = NPV^{\text{Economic}} + NPV^{\text{Eco}} + NPV^{\text{Social}} \quad (1)$$

where $NPV^{Sustainability}$ is composed of economic ($NPV^{Economic}$), eco (NPV^{Eco}) and social (NPV^{Social}) net present values (Zore et al., 2018). $NPV^{Economic}$ is defined as the surplus of revenue and salvage value of projects sold at the end of the year, reduced by expenditures and investments. In order to achieve positive economic performance in the production of renewable energy, a 2 %/y price rise of biofuels and electricity is considered. NPV^{Eco} is calculated as the difference between eco benefit (EB) and eco cost (EC), where EB represents the monetary provision for avoided investment in environmental unburdening, and EC represents the investment needed to prevent environmental burdening. NPV^{Social} is composed of the social security contributions paid by employers and employees, the social unburdening effect in the creation of new jobs and the social costs. More details regarding the $NPV^{Sustainability}$ objective and its pillars can be found elsewhere (Zore et al., 2018).

3. Large-scale case study of EU-27

This paper presents a framework that foresee a gradual reduction of GHG emissions and a gradual increase in the renewable energy share in order to achieve zero carbon emission target by 2060. The EU is divided into 47 zones, as shown in Figures 1-3, assuming that possible locations of storage and pretreatment facilities, biorefineries and power plants, and demand are close to the centre of each zone. The current share of renewable electricity and biofuels (Eurostat, 2020) that needs to be satisfied during optimization was considered for the first year. For further years, the difference between the current share of renewables (Eurostat, 2020) and the target renewables share should be satisfied by renewable energy sources, where the following transitions are investigated:

- A 50 % transition from fossil-based to renewable-based resources achieved continuously over a 20-y period (to 2040). Up to 10 % of the area could be devoted to satisfying the demand for food (100 %) and biofuels (50 %) and up to 1 % of additional area for renewable electricity (50 % of demand). Note that around 8 % of the area is already devoted to wheat and corn production (FAOSTAT, 2018).
- A 75 % share of renewable energy should be achieved over a period of 30 y (by 2050).
- Complete transition from current energy sources to renewable-based energy supply should be achieved over a time span of 40 y (in 2060).

Modelling of scenarios regarding gradual energy transition towards more renewable energy, with reduced GHG emissions, is inspired by achieving climate ambition of a two degree scenario (2DS) or even beyond (B2DS), which would require an almost complete reduction of CO_2 emissions or even a carbon negative pathway in the power sector by 2060 (IEA, 2017).

The multi-period model for the synthesis of EU-27 renewable-based supply networks consists of approximately 1,516,640 single equations, 43,706,671 single variables, and 16,732 discrete variables, and is solved in about 4 h. The problem is formulated in the modelling system GAMS version 27.2.0, and the solutions are obtained using the Gurobi solver on the HPC server DL580 G9 CTO (4 processors – 32 core, Intel® Xeon® CPU E5-4627 v2 @ 3.30 GHz, 768 GB RAM).

3.1 Results and discussion

The distribution of products across the entire EU over the next 40 y is presented in Figure 1 for distribution of gasoline substitutes, in Figure 2 for distribution of diesel substitutes and in Figure 3 for distribution of renewable electricity, where wind turbine and PV panels are selected. In all figures three maps are shown, a) for the year 2020 where current share of renewables is considered, however optimised, b) for the year 2040, where 50 % transition should be achieved and c) for the year 2060 where 100 % renewable energy should be achieved in transport and electricity sectors. For all the cases, maximal $NPV^{Sustainability}$ was used as an objective.

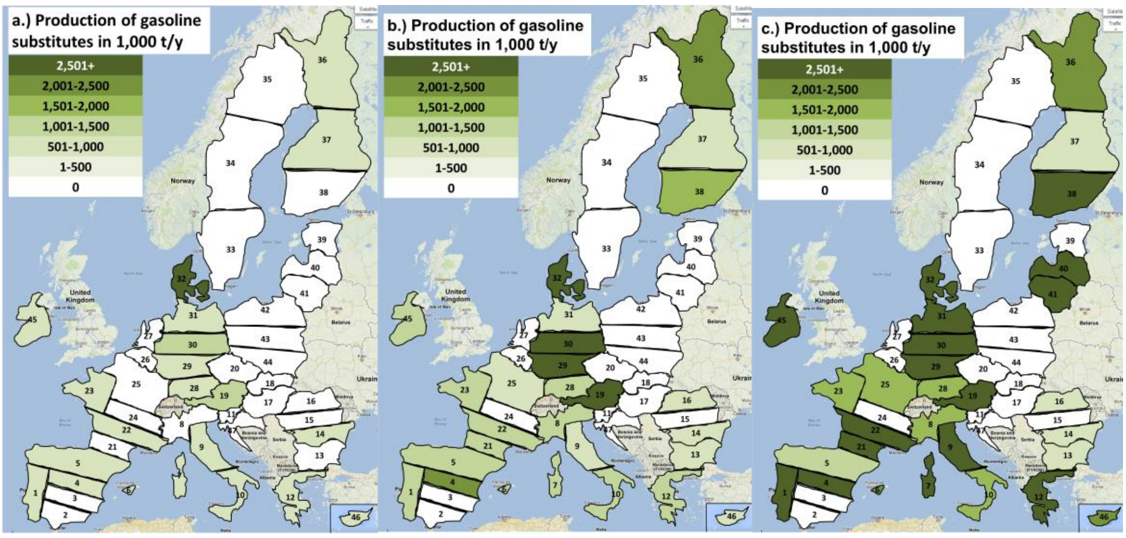

Figure 1: Distribution of gasoline substitutes production in a) year 2020, b) year 2040 and c) year 2060

Figure 1 shows that when optimizing the current share of renewable energy in the transport sector (around 10 % (Eurostat, 2020)), the production of bioethanol and green gasoline is mainly suggested in Denmark, Austria and Germany, while smaller amounts are produced also in other countries. In 2040, when the demand for biofuels increases to 50 %, an increase in capacity for the same locations is observed, and additionally new

locations in Italy, Bulgaria, France and southern Finland are suggested. In 2060, when a complete transition should be achieved, production takes place additionally in Latvia and Lithuania, while for the already suggested locations an increase in production capacity is observed. Among the suggested technologies for producing gasoline substitutes are gasification and further both, syngas fermentation and catalytic synthesis, with ethanol and hydrogen as the main products. After 2040, biochemical process for the production of bioethanol via hydrolysis of miscanthus is additionally selected to achieve a higher share of renewables.
The distribution of diesel substitutes production over the next 40 y is presented in Figure 2. Currently (current share of renewables, with optimized locations and production), production takes place mostly in the same locations as suggested for gasoline substitution because of lower investment and logistic costs if facilities for renewable gasoline and diesel production are at nearby locations. Finland, Ireland and Greece are exceptions, where it is suggested that only ethanol be produced. After 20 y, the highest increase in production of diesel substitutes is suggested in Austria, Germany and Denmark, where large amounts of FT-diesel are produced, and in central Spain, where biodiesel production from algal oil is observed to a large extent. In addition, compared to year 1 (2020), production of FT-diesel in Finland and biodiesel in Portugal, Greece and Bulgaria is proposed to meet demand. For the final year (2060), increased production capacities are suggested in the same locations, but in northern Germany and in Latvia, new biorefineries are also suggested.

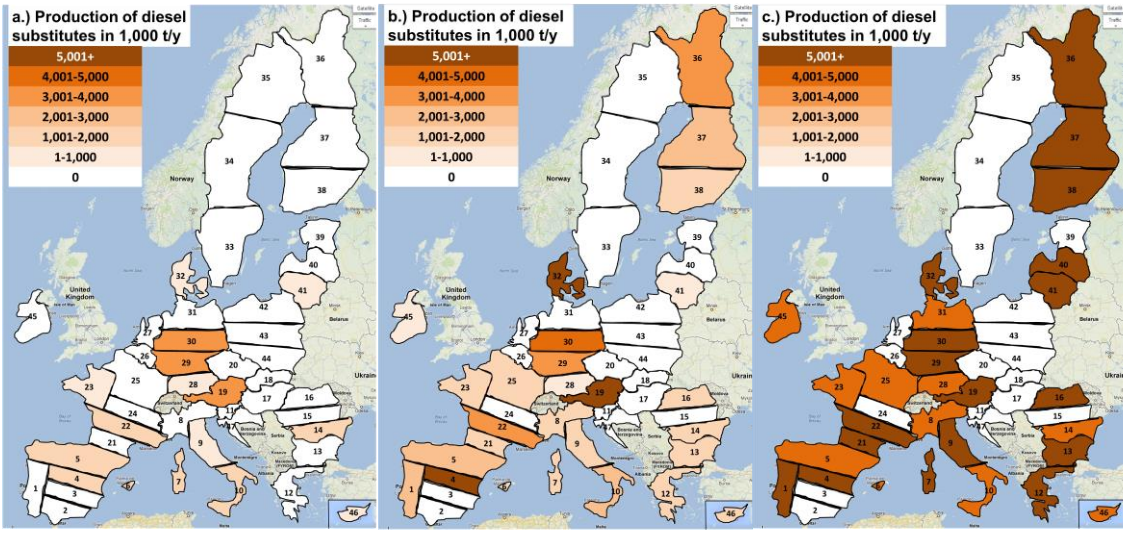

Figure 2: Distribution of diesel substitutes production in a) 2020, b) 2040 and c) 2060

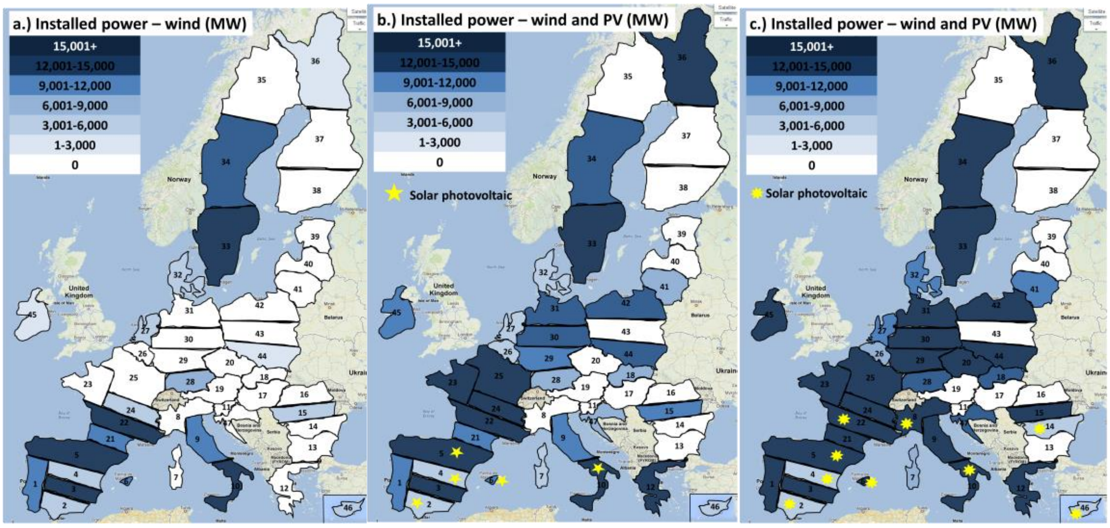

Figure 3: Distribution of wind turbines and solar photovoltaics in a) 2020, b) 2040 and c) 2060

Figure 3 shows the distribution of electricity installations and their dynamics from 2020 until 2060. The share of energy from RES in electricity consumption within the EU-27 is already relatively high (about 32 %, of which

almost half is achieved by wind and solar (Eurostat, 2020)), compared to transport, heating and cooling, where approximately 20 % consumption of renewable electricity was achieved by the end of 2018 (Eurostat, 2020).
After considering the current share of electricity from wind and solar power (around 16 %), only installations of wind turbines are suggested across the EU-27, as shown in Figure 3a. The main advantage of wind turbines over PV plants is that more electricity can be produced during winter, with better economic performance. To satisfy the current share of renewable electricity, a total of 60,895 wind turbines are installed, producing 140,058 MW of renewable electricity. Most renewable electricity is produced in Spain, Italy, France and southern Sweden. In 2040, wind turbines are suggested across entire EU, while additional PV installations are suggested in Spain and Italy (the corresponding zones are marked in Figure 3 b). A total of 145,974 wind turbines are suggested to be installed by 2040. Besides additional installations in existing locations, also new locations in Greece, Germany, Poland and France are suggested. To achieve a complete transition by 2060, it is suggested that 298,380 wind turbines and 1,458 km^2 of PV panels be installed. Additional installations are recommended at the previously suggested locations, and new locations in northern Italy and Czech Republic are proposed.
Table 1 shows the main results of optimization when maximizing $NPV^{Sustainability}$ in terms of area used, renewable electricity production, gasoline and diesel substitutes and number of employees in transition from fossil to renewable-based energy production.

Table 1: Comparison of main results of sustainability net present value optimization

Items	Year 2020	Year 2040	Year 2060
Area used (% of total)	10.22	10.53	16.84
Wind turbines (% of demand)	100.00	88.90	74.00
Solar PV (% of demand)	0.00	11.10	26.00
Ethanol (1,000 t/y)	9,030	28,796	87,175
Green gasoline (1,000 t/y)	1,436	11,551	15,636
Et-diesel* (1,000 t/y)	0.00	0.00	11,493
Me-diesel** (1,000 t/y)	18,601	21,166	25,831
FT-diesel (1,000 t/y)	0.0	49,582	129,480
Hydrogen (1,000 t/y)	1,017	2,581	9,051
$NPV^{Sustainability}$ ($1.0\cdot10^6$ €)	/	1,427,076	4,766,067
Number of employees	90,177	319,047	484,941

*Et-diesel: diesel with ethanol as catalyst, **Me-diesel: diesel with methanol as catalyst

To achieve a 50 % share of renewable energy (year 2040), 10.53 % of the area is used (11 % is considered available area), of which 9.90 % of the area is devoted to food and biofuel production or additional afforestation, while 0.63 % of the area is intended for electricity generation. In year 1 (2020), up to 3 % of the total area is suggested for afforestation, which would provide additional eco-benefits. In 2040, only 0.1 % of the area is afforested because of higher demand and production of biofuels. On the other hand, the area used for miscanthus cultivation increases from 1.1 % to 3.2 %, because of its high hectare yield and low price, and good economic perspective. In the final year, 15.45 % of the area is required for food and biofuel production, while 1.39 % of the area is needed for electricity generation.
In the first year, biodiesel production is suggested, using algal oil as a feedstock, if algae are available in the region; otherwise the production from waste cooking oil by transesterification with methanol is suggested. The production of FT-diesel gradually increases, and by 2040 it satisfies about 70 % of the demand ($49.58\cdot10^6$ t/y), and the remainder is replaced by biodiesel ($21.17\cdot10^6$ t/y). In the case of gasoline substitutes, ethanol is suggested as the main product in all years. The demand for renewable electricity is completely satisfied in the first year by wind power, while in later years, installation of PV panels is suggested (as explained before and shown in Figure 3), from which 26 % of renewable electricity is produced in the final year, when a 100 % share of renewables is targeted.
Another important product is hydrogen, which is produced by gasification and water gas shift reaction using membrane separation (Martín and Grossmann, 2011), and as a by-product in other conversion technologies. The production of hydrogen increases over the years, which is also economically advantageous because of its higher selling price compared to other products. In 2060, $9.05\cdot10^6$ t/y of hydrogen is produced.
The transition to renewable energy is expected to affect the social pillar of sustainability, whereby new jobs will be generated. In the final year, 484,941 employees will be required, mainly in the construction and manufacturing sectors for the production of electricity.
The objective value ($NPV^{Sustainability}$) in 2040 is $1,427.08\cdot10^9$ €, of which $NPV^{Economic}$ is $664.11\cdot10^9$ €, NPV^{Eco} $697.04\cdot10^9$ € and NPV^{Social} $0.065\cdot10^9$ €. In 2050, the $NPV^{Sustainability}$ increases to $2,237.42\cdot10^9$ €, and in 2060, to

4,766.07·10^9 €. In all years, economic and environmental pillars contribute more to sustainability than the social pillar.

4. Conclusions

This study presents a mathematical programming approach for the synthesis of renewable supply networks, which include the production of food, biofuel, electricity, hydrogen and other by-products from renewable sources. The methodology was applied to a case study of the EU-27 and a multi-period MILP model is proposed, with sustainability net present value as an objective, from which compromise economically, environmentally and socially beneficial designs are obtained. The prospects of the EU in transition from fossil to renewable-based production of energy and bioproducts are discussed.
To achieve a complete transition in the next 40 y, a combination of various technologies should be used, however additional area needs to be dedicated. With respect to electricity generation, foreseeable demand can be met by wind turbine installations, combined with PV panels in later years. To create a more sustainable future, the bulk of the transformation to renewable-based supply should occur in the transport sector, where the lowest share of renewables of all sectors has been achieved thus far. As a gasoline substitute, bioethanol is proposed, while as a diesel substitute, biodiesel is suggested, and for a complete transition, production of FT-diesel is proposed. We conclude that the transition to renewable energy production is sustainable and economically feasible in the long-term. However, it should be noted that the prices of biofuels consider the same excise duties as those on petroleum fuels, and the price of electricity is also fixed. In the future, emphasis will be placed on the deployment of electricity storage in the energy system.

Acknowledgements

The authors would like to acknowledge financial support from the Slovenian Research Agency (PhD research fellowship contract No. 1000-19-0552, core research funding No. P2-0032 and P2 0412 and projects J7-1816 and N2-0138).

References

Banja M., Sikkema R., Jégard M., Motola V., Dallemand J.F., 2019, Biomass for energy in the EU–The support framework, Energy Policy, 131, 215-228.

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

Čuček L., Zore Ž., Krajačić G., Martín M., Grossmann I., Boldyryev S., Kravanja Z., 2016, Synthesis of renewable energy supply networks considering different frequencies of fluctuations in supply and demand, 2016 AIChE Annual Meeting, San Francisco, CA, USA, paper 760d.

Elshout P.M., van Zelm R., van der Velde M., Steinmann Z., Huijbregts M.A., 2019, Global relative species loss due to first-generation biofuel production for the transport sector, GCB Bioenergy, 11(6), 763-772.

Eurostat, 2020, SHARES 2018 summary results (Short assessment of renewable energy sources), <ec.europa.eu/eurostat/web/energy/data/shares>, accessed 12.3.2020.

FAOSTAT, 2018, Crops, <fao.org/faostat/en/#data/QC/>, accessed 10.3.2020.

Ghosh P., Westhoff P., Debnath D., 2019, Biofuels, food security, and sustainability. In: Debnath D., Babu S. (Eds.), Biofuels, Bioenergy and Food Security. Technology, Institutions and Policies, Elsevier, San Diego, United States, 211-229.

IEA, 2017, Energy technology perspectives 2017, <iea.org/reports/energy-technology-perspectives-2017>, accessed 25.5.2020.

IRENA, 2018, Global Energy Transformation: A roadmap to 2050; International Renewable Energy Agency, <irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf>, accessed 14.4.2020.

Lam H.L., Klemeš J.J., Kravanja Z., 2011, Model-size reduction techniques for large-scale biomass production and supply networks, Energy, 36(8), 4599-4608.

Martín M., Grossmann I.E., 2011, Energy optimization of hydrogen production from lignocellulosic biomass, Computers & Chemical Engineering, 35(9), 1798-1806.

Martín M., Grossmann I.E., 2013, On the systematic synthesis of sustainable biorefineries, Industrial & Engineering Chemistry Research, 52(9), 3044-3064.

Owusu P.A., Asumadu-Sarkodie S., 2016, A review of renewable energy sources, sustainability issues and climate change mitigation, Cogent Engineering, 3(1), 1167990.

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