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Biogas Supply Chain Optimization Considering Different Multi-Period Scenarios

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This research involves the multi-period optimization of an agricultural-type biogas supply network to produce electricity, heat and organic fertilizer. A mixed-integer linear programming (MILP) model utilizing a four-layer biogas supply chain is put forward. The model accounts for biogas plants based on two different guaranteed electricity purchase prices depending on capacity (up to 999 kW and up to 4,999 kW) and on hourly auction trading prices. In case of fixed electricity prices, monthly periods are considered, while in the case of market prices, variability on an hourly basis is accounted for. An illustrative case study of agricultural biogas plants in Slovenia where up to three biogas plants could be selected was modelled. Technologies could include an anaerobic digester, press-based dewatering and a combined heat and power plant (CHP), while water, electricity, and heat required for the anaerobic digestion plant itself could be “recycled”. Four scenarios are presented based on different electricity prices and market price variability. The first two scenarios based on monthly time periods consider guaranteed purchase prices of electricity (206 $/MWh for biogas plants up to 999 kW capacity and 187 $/MWh for biogas plants up to 4,999 kW capacity), while the last two scenarios consider auction trading prices changing every hour at different biogas production capacities, and thus the model is based on hourly time periods. The first two scenarios showed three biogas plants with profit after tax of 663,624 $/y and 6,089,559 $/y with various dry matter contents ranging from 4.2 to 13 %. Alternatively, the last two scenarios showed losses incurred with optimal dry matter contents close to 13 %. This study provides the answers to the effects of realistic hourly variation in electricity price on a biogas supply chain network in comparison to subsidized prices based on monthly time periods.

1. Introduction

Biomass energy is the predominant source of renewable energy available today but still, large portions of it remain untapped. In addition, this same biomass energy, alternatively called bioenergy, represents approximately 10 % of the energy consumed globally today (Central Statistics Office, 2017). Against this backdrop, during the 2017 United Nations Climate Change conference held in Bonn, Switzerland, renewed concerted calls were posited to increase the incorporation of renewable energy in the global community’s energy mix (UNCC, 2017). Increased bioenergy use for electricity generation or automobile fuel transportation is viewed as a viable option to mitigating global warming, increasing energy security, and increasing waste management potentials while creating employment in rural or peri-urban areas (Yue et al., 2014). Sustainably incorporating bioenergy in any energy mix needs robust supply chain networks.

Most of the studies performing optimization of biorefinery supply chains networks have been carried out on yearly (Sy et al., 2018) and monthly and yearly basis (Čuček et al., 2014); while few studies also considered future years and shorter time periods. Most of the existing studies also involve networks that operate on a single capacity level (Yue et al., 2014). This study extends the work by Egieya et al. (2018), who made use of a four-layer biogas supply chain network (see Figure 1) methodology and considered only guaranteed purchase prices

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of electricity at a single capacity level of 999 kW_{el}. In this work variations in biogas plant capacities are considered while accommodating hourly, daily and monthly optimization basis and scenarios for both subsidised and auction trading prices. Storage of biogas is also considered to enable electricity production at higher prices, while simultaneously storing biogas when electricity prices are low. In order to reduce the model size and shorten computational time, the number of time periods considered is just three periods per day (8 h/period), while all the days in each month are delineated based on the days of the week.

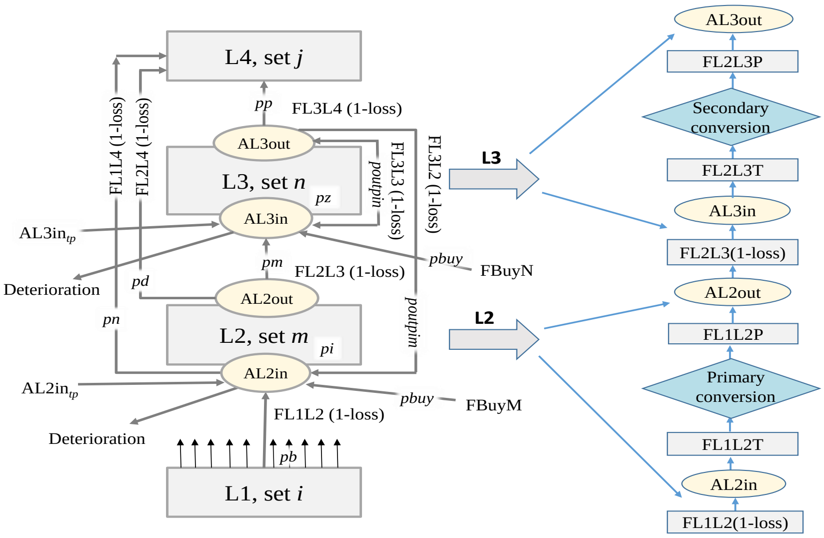

Figure 1: Four-layer supply network design (after Egieya et al., 2018)

2. Model description

2.1 Description of Biogas Supply Chain

The biogas supply network (Figure 1) consists of four layers with the network's features as in Egieya et al. (2017). The first layer (L1) is the harvesting and collection zone, which contains the set *pb* of biomass feedstocks (corn, wheat and triticale grains, straw and silage) and different manure types (cattle, pig and poultry manure, poultry bedding and slurry) located in site *i.* The transportation modes considered to ship these feedstocks *pb* to anaerobic digesters (L2) located in site *m* are road (truck) and pipelines. In the second layer (L2), primary conversion of *pi* (sum of biomass and waste feedstocks *pi*, recycled products *poutpim* and purchased products *pbuy*) occurs. These are converted to intermediate products *pm* (biogas and wet digestate) or final products *pd* using given conversion factors. These intermediate products *pm* or *pd* could be temporarily stored before further shipment to layer 3 (L3) or 4 (L4). After storage, the products become products *pz,* which are the sum of intermediate products *pm*, recycled product *poutpin* and purchased products *pbuy*. They are further converted (using conversion factors) to the desired products *pp* (electricity and dry digestate). The technologies considered in L3 are combined heat and power (CHP) plants and physical dewatering. Road, pipeline and transmission lines are considered as transport modes to convey *pp* products to the demand zone located in Layer 4 (L4). In addition, certain products (heat and electricity from CHP and water from dewatering) could be recycled within the supply chain. *Poutpin* represents materials recycled within the conversion facilities located in site *n* while *poutpim* shows materials recycled to anaerobic digesters located in site *m*. For sustainable supply of all materials within the supply chain, four storage facilities are also modelled. Characteristics of biomass and waste feedstocks such as different dry matter contents, methane contents and biogas yields are accounted for and are obtained from the Agriculture Institute of Slovenia (2008). Furthermore, seasonality of the agricultural feedstocks and different yields are considered. Different electricity prices are applied, guaranteed purchase prices which are fixed and are retrieved from the Government of the Republic of Slovenia for Legislation (2017) and auction trading prices which change every hour and are obtained from the BSP Energy Exchange (2018).

2.2 Model development

The model developed follows the same formulation sequence as that of Egieya et al. (2018) which includes material and energy balances, pre-treatment and conversion constraints and cost correlations. The model formulated is based on mixed-integer linear programming (MILP) with the objective of maximizing profit after tax (P_A) shown in Eq. 1 from the generation of electricity, heat and digestate within the biogas supply network:

$$P_A = (1 - t_P) \cdot P_B = (1 - t_P) \cdot (R^{Total} - C^{Total}) \tag{1}$$

where t_P is tax rate, P_B is profit before tax (\$/y), R^{Total} is total revenue accrued (\$/y) and C^{Total} is total cost incurred in the supply chain (\$/y). A discount rate of 8 %, a lifetime of 15 y and the tax on the profit of 19 % are considered. Calculation of the total revenue (T^{Total}) is put forward by Eq. (2):

$$\begin{aligned} R^{Total} = & \sum_{m\in M} \sum_{j\in J} \sum_{pd\in PD} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{L2,L4},net}_{m,j,pd,mp,dp,hp} \cdot P_{pd,mp.dp,hp} + \\ & \sum_{n\in N} \sum_{j\in J} \sum_{pp\in PP} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{L3,L4},net}_{n,j,pp,mp,dp,hp} \cdot P_{pp,mp,dp,hp} + \\ & \sum_{m\in M} \sum_{j\in J} \sum_{pn\in PN} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{L1,L4},net}_{m,j,pn,mp,dp,hp} \cdot P_{pn,mp,dp,hp} \end{aligned} \tag{2}$$

where *hp*, *dp*, and *mp* are hourly, daily and monthly periods. *DPM* stands for the set of pairs of days and months (1st month has 31 days, 2nd month has 28 days and so on). $F^{\mathrm{L3,L4},net}_{n,j,pp,mp,dp,hp}$ represents the flow of produced products *pp* (electricity, heat and dewatered digestate) from the plant *n* to demand *j*. $F^{\mathrm{L2,L4},net}_{m,j,pd,mp,dp,hp}$ represents the flowrate of direct product *pd* (wet digestate) produced from anaerobic digestion at site *m* and sold as fertilizer in site *j* to farmers. $F^{\mathrm{L1,L4},net}_{m,j,pn,mp,dp,hp}$ represents materials (*pn*) produced in site *i* shipped directly to the demand zone in site *j*. $P_{pd,mp,dp,hp}$, $P_{pp,mp,dp,hp}$ and $P_{pn,mp,dp,hp}$ are prices of direct products (*pd*), produced products (*pp*) and products that do not undergo treatment (*pn*).

Total costs accrued (C^{Total}) in the biogas supply chain network are a sum of costs for feedstocks, additional costs of feedstocks if they are transported out of the zone, purchase of additional materials needed in L2 and L3, shipment (TC_p^{Total}), storage (SC_p), labour (*LC*), depreciation (*DCC*), maintenance (*MC*), and miscellaneous cost (*MSC*) as displayed in Eq. (3):

$$\begin{aligned} C^{Total} = & \sum_{i\in I} \sum_{pb\in PB} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} PR_{i,pb,mp,dp,hp} \cdot c_{pb,mp} + \\ & \sum_{i\in I} \sum_{pb\in PB} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{L1,L2}}_{i,m,pb,mp,dp,hp} \cdot c^{add}_{i,m,pb,mp} + \\ & \sum_{m\in M} \sum_{pbuy\in PBUY} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{buy,L2}}_{m,pbuy,mp,dp,hp} \cdot c_{pbuy,mp} + \\ & \sum_{n\in N} \sum_{pbuy\in PBUY} \sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in HP} \Big|_{(dp,mp)\in DPM} F^{\mathrm{buy,L3}}_{n,pbuy,mp,dp,hp} \cdot c_{pbuy,mp} + \sum_{p\in P} TC_p^{Total} + \sum_{p\in P} SC_p + LC + DCC + MC + MSC \end{aligned} \tag{3}$$

where $c_{pb,mp}$ and $c_{pbuy,mp}$ are cost (\$/t or \$/MWh) for feedstock acquired (*pb*) and purchased materials (*pbuy*) and $c^{add}_{i,m,pb,mp}$ (\$/t) is additional cost for feedstocks *pb* if they are transported out of the zone. $PR_{i,pb,mp,dp,hp}$ is total quantity of feedstocks harvested at site *i* and shipped to storage at a primary conversion location, $F^{\mathrm{L1,L2}}_{i,m,pb,mp,dp,hp}$ represents the flowrate of feedstocks *pb* shipped from site *i* to plant location *m* in different zone, while $F^{\mathrm{buy,L2}}_{m,pbuy,mp,dp,hp}$ and $F^{\mathrm{buy,L3}}_{n,pbuy,mp,dp,hp}$ are quantities of additional raw materials purchased in L2 and L3 within a given monthly, daily and hourly period.

To reduce computational time, certain model reduction techniques are applied (Lam et al., 2011). Instead of 24 hours a day, three parts of the day have been used (H1: 6 am – 2 pm; H2: 2 pm – 10 pm; H3: 10 pm – 6 am), and instead of 28 – 31 days a month, days are represented based on the days of the week (D1: $\{d_1, d_8, d_{15}, d_{22}, d_{29}\}$, D2: $\{d_2, d_9, d_{16}, d_{23}, d_{30}\}$, D3: $\{d_3, d_{10}, d_{17}, d_{24}, d_{31}\}$, D4: $\{d_4, d_{11}, d_{18}, d_{25}\}$, D5: $\{d_5, d_{12}, d_{19}, d_{26}\}$, D6: $\{d_6, d_{13}, d_{20}, d_{27}\}$, D7: $\{d_7, d_{14}, d_{21}, d_{28}\}$). As the electricity market prices are provided on an hourly basis, they are averaged, see Eq. (4).

$$\begin{aligned} P_{electricity,mp,dp,hp} = & \frac{\displaystyle\sum_{mpo\in MP} \sum_{dpo\in DP} \sum_{hpo\in HP} \Big|_{\wedge(mpo,mp)\in MPOM \wedge (hpo,hp)\in HPOH \wedge (dpo,dp)\in DPOD \wedge (dpo,mpo)\in DPM} P_{electricity,mpo,dpo,hpo}}{\displaystyle\sum_{mpo\in MP} \Big|_{(mpo,mp)\in MPOM} |mpo| \cdot \sum_{dpo\in DP} \sum_{(dpo,mp)\in DPM} \Big|_{(dpo,dp)\in DPOD} |dpo| \cdot \sum_{hpo\in HP} \Big|_{(hpo,hp)\in HPOH} |hpo|}, \\ & \forall mp \subseteq MP, dp \subseteq DP, hp \subseteq HP \end{aligned} \tag{4}$$

where *MPOM*, *DPOD* and *HPOH* represent set of pairs of maximal number of time periods in a year (*mpo*, *dpo* and *hpo*) and merged time periods (*mp*, *dp* and *hp*). *HPOH* splits 24 hours in a day into 3 shift periods (morning, afternoon and night; H1-H3) while *DPOD* is split into 7 shift periods (Monday – Sunday; D1-D7).

3. Case study

The model is implemented on a hypothetical case study considering three zones in Slovenia (see Figure 2). Three locations each are put forward for the harvesting and collection sites, primary conversion, secondary conversion and demand. It is assumed that the primary conversion facilities (anaerobic digesters) are 100 m away from the secondary conversion facilities (CHP and belt press dewatering). The total area for each harvesting site is 250 km^2, while 50 % (Site I and II) and 37 % (Site III) of the total area is available for growing agricultural crops. For all data, the exchange rate of 1.33 EUR/USD is used as in Egieya et al. (2017).

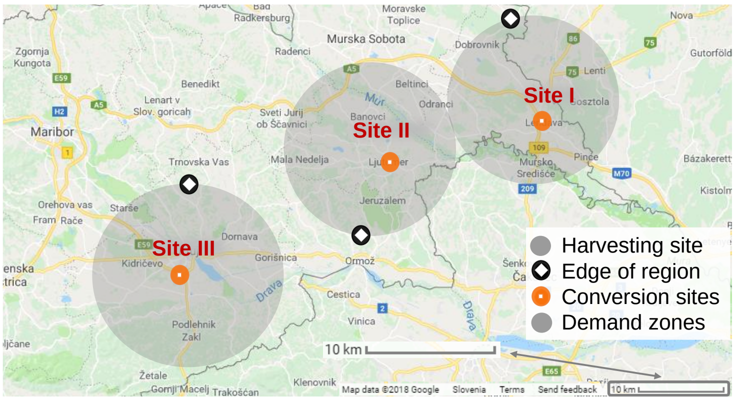

Figure 2: Region in case study (from Google Maps, 2018)

To test the effectiveness of the model, four scenarios (SC 1 – SC4) are modelled: i) SC 1 considers a guaranteed electricity purchase price of 206 $/MWh with capacity up to 999 kW; ii) SC 2: guaranteed electricity purchase price of 187 $/MWh with capacity up to 4,999 kW; iii) SC 3: hourly-based auction trading prices with demand for methane between 1.95×10^6 and 2.38×10^6 m^3/y (average 0.9 – 1.1 MW of electricity produced) and iv) SC 4: hourly-based prices with demand for methane between 9.76×10^6 and 11.93×10^6 m^3/y (average 4.8 – 5.2 MW of electricity produced). Hourly-based electricity prices are based on 2017 prices, ranging from -57.1 and 264.7 $/MWh (BSP South Pool Energy Exchange, 2018).

The models based on monthly-time periods (SC 1 and SC 2), consist of approximately 19,700 single equations, 30,700 single variables and 774 binary variables and are solved in a few seconds. On the other hand, models based on hourly time periods (SC 3 and SC 4) containing 12 monthly, 7 daily and 3 hourly time periods comprise 259,935 equations, 289,910 single variables and 684 binary variables and are solved in few hours. In all the scenarios the zero optimality gaps is used.

Table 1 presents the main results obtained from the four scenarios considered. The best solution is obtained when all three possible plants are selected with a capacity of up to 4,999 kW of electricity. SC 2 shows the highest profit (6,089,560 $/y), lowest payback time (3.6 y), highest amounts of electricity sold to the grid (121.6 GWh/y) and largest total quantity of feedstocks used (406,928 t/y). SC1 is also economically viable with three plants selected but shows a payback time of 6.0 y, 24.3 GWh/y of electricity sold, and 72,005 t/y of total raw materials used. Significant differences between SC 1 and 2 are in average dry matter content in fermenters (13.00 vs 4.40 %). In SC 1 mainly corn silage, poultry manure and bedding and smaller amounts of cattle manure are used, while in SC 2 mainly cattle and pig manure, poultry slurry, grass and wheat silage, glycerol and triticale grains are added to the selected feedstocks as used in SC 1. On the other hand, when market prices are considered, economic loss is accrued when the demand for methane is specified, while no production takes place if the demand is not specified. Hence, in SC 3 plant I is selected while plant III is selected in SC 4 with capacities of 1 MW and 5 MW. Furthermore, in both scenarios, the dominant feedstocks selected are corn silage and poultry manure, with smaller capacities of wheat silage and poultry bedding. Dry matter (DM) content is around 13 %. A significant part of the renewable electricity generated is reused in SC 3 and 4, while in SC 1 and 2 all the electricity needed for the plants is purchased from the grid.

It is worth stating that in all scenarios, the optimal transportation mode which support the profit after tax objective shows that: from L1 to L2, road transport by truck is selected; from L2 to L3, both biogas and wet digestates produced are shipped using pipelines; from L3 to L4, dry digestate is transported using trucks while electricity and heat are transmitted through transmission lines and pipelines; Recycling of water from dewatering plants and heat from L3 to L2 occurs using pipelines, and electricity through transmission lines (SC 3 and 4).

Figure 3 presents a closer look at the breakdown of costs incurred in SC 1 – 4. The dominant cost in SC 1 and 3 occurs in the form of depreciation costs (about 29.9 % and 31.4 % of total cost) while feedstock acquisition cost is dominant in SC 2 and 4 (40.7 and 29.9 %). The results also show that averaging electricity prices based on 7 periods a month alleviate the variability of electricity prices, and SC 3 and 4 produced electricity at constant capacity while biogas storage was not selected.

Table 1: Main results from scenarios

	SC 1*	SC 2*	SC 3	SC 4
Feedstock (t/y)				
Cattle manure	206	155,626	/	/
Corn silage	22,032	37,375	6,185	24,469
Glycerol	/	2,259	/	/
Grass silage	/	62,303	/	/
Pig manure	/	24,576	/	/
Poultry bedding	32,080	32,169	/	53
Poultry manure	17,688	17,157	14,053	70,203
Poultry slurry	/	47,181	/	/
Wheat silage	/	5,044	/	6,446
Triticale grains	/	13,289	/	/
Water purchased | recycled	/ | 41,987	/ | 1,373,901	4,016 | 15,746	21,749 | 84,099
Products (sold)				
Digestate (23 % dry solids, t/y)	50,689	193,509	18,280	92,606
Electricity (MWh/y)	24,330	121,648	6,861	34,326
Heat (MWh/y)	16,005	80,027	4,872	24,375
Utilities required (MWh/y)				
Electricity purchased | “recycled”	1,953 | /	9,764 | /	151 | 435	756 | 2,174
Heat purchased | “recycled”	/ | 4,638	/ | 23,190	/ | 1,391	/ | 6,958
DM content (%)	13.00	4.40	13.00	12.72
Economic results				
Revenue | expenditure (10^6 $/y)	6.03 | 3.66	29.89 | 17.91	0.78 | 1.07	3.88 | 3.89
Investment (10^6 $)	13.32	38.20	4.18	10.95
Profit after tax (10^6 $/y)**	0.66	6.09	-0.78	-1.28
Payback time (y)	6.0	3.6	/	/
Selected plants	I, II, III	I, II, III	I	III

*results represent sum / average values from three plants

**tax from corporate income of 19 % is assumed. It depends on the achieved positive operating profit

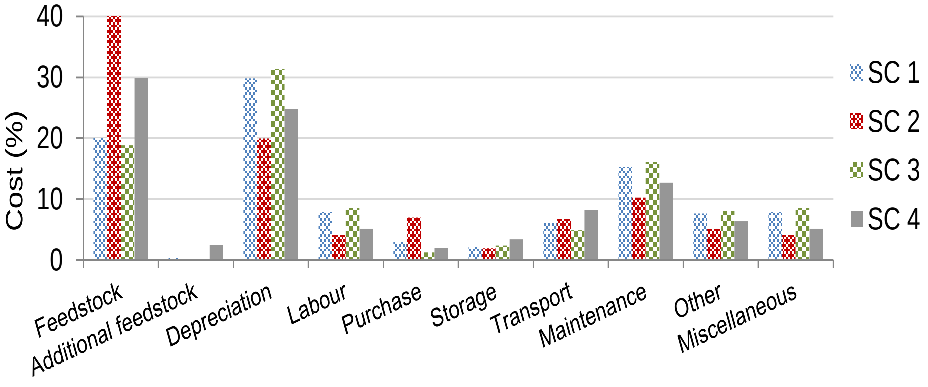

Figure 3: Cost breakdown in scenarios 1 – 4

An additional scenario is performed where for a selected month (e.g. January) the hours are merged into 3 shift periods. Biogas storage is also not selected because of higher investment cost for CHP, biogas holder and use of external heating when electricity and heat are not produced. Figure 4 presents the electricity production in SC 3 for January, where the base case scenario investment in biogas holder is reduced to 300,000 $ for 3,000 m^3 of biogas stored. From Figure 4, the peak electricity produced is about 9.4 MWh/period or 1.173 kWh/h. Peak electricity load is generated from the biogas plant mainly during the H2 period (2 – 10 pm) and mostly also during the H1 period (6 am to 2 pm). Figure 4 also shows that during the H3 period (10 pm – 6 am), there is limited electricity production from biogas plants. It should also be noted that the electricity produced and the amount of biogas stored significantly depends on investment cost for biogas holder.

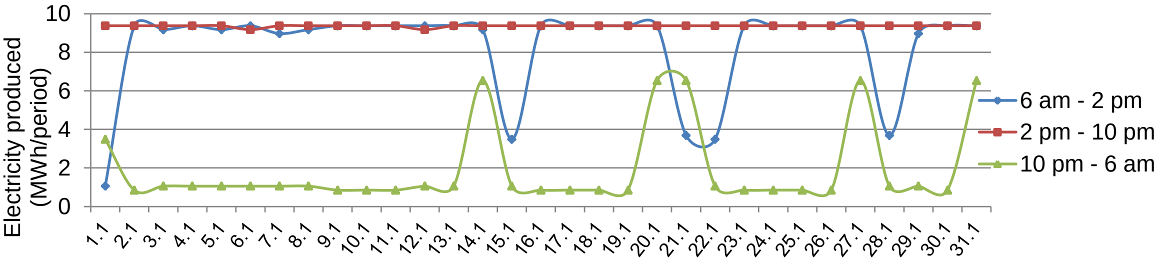

Figure 4: Electricity produced in each day in a specific month (January)

4. Conclusions

A MILP model has been implemented on a biogas supply chain network for an illustrative case study in Slovenia. Electricity, heat and dry digestate were produced on hourly, daily and monthly basis. In the four scenarios considered, poultry manure and corn silage were selected as part of the optimal feedstocks. Using auction trading prices on an hourly basis (SC 3 and SC 4) shows no profitability in the supply chain, which was a result of no government intervention (subsidies). The model shows prospects of being a good decision support tool in both public and private organizations in forecasting electricity production. In subsequent research, the model will consider other renewable energy sources while increasing the objectives to environmental and social perspectives. It would also be interesting to analyse the effects of electricity storage in batteries, electric cars and in district heating networks when the price of electricity is low. Finally, opportunities to improve profitability of biogas production processes will be implemented in the model.

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References

Agriculture Institute of Slovenia, 2008, Biogas substrates in Slovenia <arhiv.kis.si/datoteke/File/kis/SLO/MEH/Biogas/substratna_lista_2008.pdf> accessed: 17.5.2018.

BSP South Pool Energy Exchange, 2018, Day-ahead Trading Results - SI <www.bsp-southpool.com/day-ahead-trading-results-si.html> accessed: 17.5.2018.

Central Statistics Office, 2017, The IEA Key World Energy Statistics <webstore.iea.org/key-world-energy-statistics-2017> accessed: 14.02.2018.

Čuček L., Martín M., Grossmann I.E., Kravanja Z., 2014, Multi-period synthesis of optimally integrated biomass and bioenergy supply network, Computers & Chemical Engineering, 66, 57-70.

Egieya J., Čuček L., Isafiade A., Kravanja Z., 2017, Synthesis of Supply Networks over Multiple Time Frames: A Case Study of Electricity Production from Biogas, in: Espuña, A., Graells, M., Puigjaner, L. (Eds.), Computer Aided Chemical Engineering, Elsevier, 1447-1452.

Egieya J., Čuček L., Zirngast K., Isafiade A., Pahor B., Kravanja Z., 2018, Synthesis of Biogas Supply Networks using various Biomass and Manure Types, Computer and Chemical Engineering, under review.

Google Maps, 2018 <maps.google.com> accessed: 16.5.2018.

Government of the Republic of Slovenia for Legislation, 2017, Decree on support for electricity generated from renewable energy sources <www.pisrs.si/Pis.web/pregledPredpisa?id=URED4718#> accessed: 6.1.2018 (in Slovenian).

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

UNCC, 2017, United Nations Climate Change Conference in Bonn, Germany. <unfccc.int/meetings/bonn_nov_2017/meeting/10084.php> accessed: 25.2.2018.

Sy C.L., Ubando A.T., Aviso K.B., Tan R.R., 2018, Multi-objective target oriented robust optimization for the design of an integrated biorefinery, Journal of Cleaner Production, 170, 496-509.

Yue D., Slivinsky M., Sumpter J., You F., 2014, Sustainable Design and Operation of Cellulosic Bioelectricity Supply Chain Networks with Life Cycle Economic, Environmental, and Social Optimization, Chemical Engineering Transactions, 53, 4008–4029.