CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976170

Synthesis of Solar Thermal Network for Domestic Heat Utilization

Ben Abikoye[a], Lidija Čuček[b,*], Adeniyi Jide Isafiade[a], Zdravko Kravanja[b]

[a]Department of Chemical Engineering, University of Cape Town, Private Bag X3, Rondebosch 7701, Cape Town, South Africa
[b]Faculty of Chemistry and Chemical Engineering, University of Maribor, Smetanova ulica 17, 2000 Maribor, Slovenia
lidija.cucek@um.si

Strategic and systematic integration of solar thermal in the building sector can lead to energy security and emission reduction. The impact of such renewable energy application could be boosted when an integration scheme is formulated by considering the changing meteorological conditions and periodic variabilities in the profile of heat demand. The efficiency of such networks could be enhanced by incorporating heat storage technology and backup utility system to form an integrated design. In this paper, a new approach based on multi-period Mixed-Integer Non-Linear Programming (MINLP) which captures such features is developed for integrating solar thermal with the space heat and hot water supply network of a cluster of buildings. The integration scheme is implemented and solved in GAMS and considers the hourly changes in solar irradiation and ambient temperatures, together with the effects of these changes on integration variables across different time horizons. Two scenarios are considered, the first involves four winter months while the second entails four summer months. The results obtained show that solar thermal satisfies 7.4 % of the total heat required in the winter months, while it fully supplies the total heat demand in the winter months.

1. Introduction

Apart from the industrial sector, the building sector has a major share in global energy consumption, and by extension, it is one of the largest single contributors to climate change and CO_2 emissions. Energy use in buildings currently has a share of about 32 % of the total global energy consumption (UNEP, 2014). Between 60 – 80 % (depending on specific climate zone) of this share of energy is used for heating hot water, space dwellings and for cooking. A large portion of these heating is currently being accomplished using energy from non-renewable sources (EIA, 2013). Going by the trends, it is predicted that the share of carbon emissions in the building sector will likely increase by the end of the current decade (Le Quéré et al., 2016). A great opportunity exists for emission reduction in the building sector by integrating renewable energy technologies to either supplement or substitute the use of fossil energy in meeting various thermal needs.

Solar thermal is one of the most proven renewable energy sources that could be useful for hot water and space heating in residential and commercial buildings. Its strategic integration in buildings, especially for hot water supply, has been described as one of the most feasible and economical means of utilizing solar energy (Dehghan et al., 2011). To this effect, several techniques for integrating solar thermal in buildings have been reported in the literature with a demonstration of diverse mature technologies which have been advanced and commercialised over the years.

Various aspects of the most recent applications of solar hot water systems have been presented (Kee et al., 2018). Several design implementations and applications of solar thermal for space and water heating in buildings could also be found in the literature, especially for moderate temperature levels such as those required in residential and commercial buildings (Saini et al., 2017). To the best of author's knowledge, the profiles of hot water and space heat demand/consumption, as well as the general thermal energy supply patterns, have been based on assumptions using synthetic demand profiles or arbitrary values derived by some rule of thumb. This is also supported by Fuentes et al. (2018), where similar submissions were made in their study on the review of domestic hot water consumption profiles for buildings. However, factors such as seasonality and specific period/time of day play vital roles in space heating and hot water demand. A better understanding of energy use

Paper Received: 12/07/2019; Revised: 25/07/2019; Accepted: 26/07/2019
Please cite this article as: Abikoye B., Cucek L., Isafiade A.J., Kravanja Z., 2019, Synthesis of Solar Thermal Network for Domestic Heat Utilization, Chemical Engineering Transactions, 76, 1015-1020 DOI:10.3303/CET1976170

patterns (which is also subject to changes) and the influence of the changing meteorological conditions are crucial to establish a more robust solar energy integration model. Another notable observation from the literature review is that design and optimization methods which combine space heating and solar hot water supply system with thermal storage in a multi-building heat demand network are still lacking, especially in the case where the multi-building heat demand network is also characterized by varied individual profile of heat demand from one building to another. Within the framework of the European Renewable Energy Research Centres Agency (EUREC, 2013) supported by the solar heating and cooling (SHC) project document on space heating and domestic hot water (Davidson et al., 2013), building-integrated solar thermal concepts such as the one proposed in this paper has been identified as a path to achieving more energy-efficient buildings and emission reduction. In this paper, an integrated inter-building solar heat network design is presented with opportunities for periodic storage of solar thermal and backup utility system to satisfy hot water and space heating needs of the buildings. The work is formulated as a simultaneous multi-period MINLP by adapting some of the features from the study on the integration of solar thermal for industrial applications (Abikoye et al., 2019). In this current contribution, solar collectors installed on the rooftop of different types of buildings (ranging from a single-family home to multi-family apartments) generate heat energy to satisfy the thermal needs of the buildings. In the likely event that solar radiation may not be enough or available, an additional source of heat is provided for the storage tank to either heat up the freshwater from its supply temperature or to raise the temperature level of solar pre-heated water to the target temperature required in the buildings.

2. Methodology

2.1 Description of solar heat network design for applications in buildings

The framework for the integrated solar thermal network for utilization in residential sectors presented in this paper is developed to demonstrate the possibility of using harvested solar thermal to provide hot water, and space heating in three buildings denoted as VSS1, ESS1 and ESS2 (see Figure 1). Solar collectors absorb the incident flux from the sun through its surface, and in the process, raise the temperature of the heat transfer fluid. In this study, water is considered as the heat transfer fluid across the integrated system with a specific heat capacity of 1.16 kWh/(t°C) and a density of 1 t/m^3. The heated water flows across the collectors to the storage tank where it exchanges heat. It is further channelled to provide hot water and space heat for the buildings. In the proposed design, hot water consumption of the three buildings in the network is linked to fresh water supply in the first storage tank (Tank 1) for replenishment. Then, depending on the temperature level of harvested solar thermal, hot water can be supplied directly to the buildings from Tank 1 through a bypass or through the second storage tank (Tank 2) for additional heating in situations where the required temperature level is not reached. Furthermore, additional heating source is provided as a backup for Tank 2 while Tank 1 keeps functioning as a preheating source. It should be noted that Tank 1 is heated only when temperature in the tank is lower than temperature of the circulating water and thus in order to efficiently utilise solar thermal energy, Tank 2 is suggested and is further heated by backup utility to the required temperature.

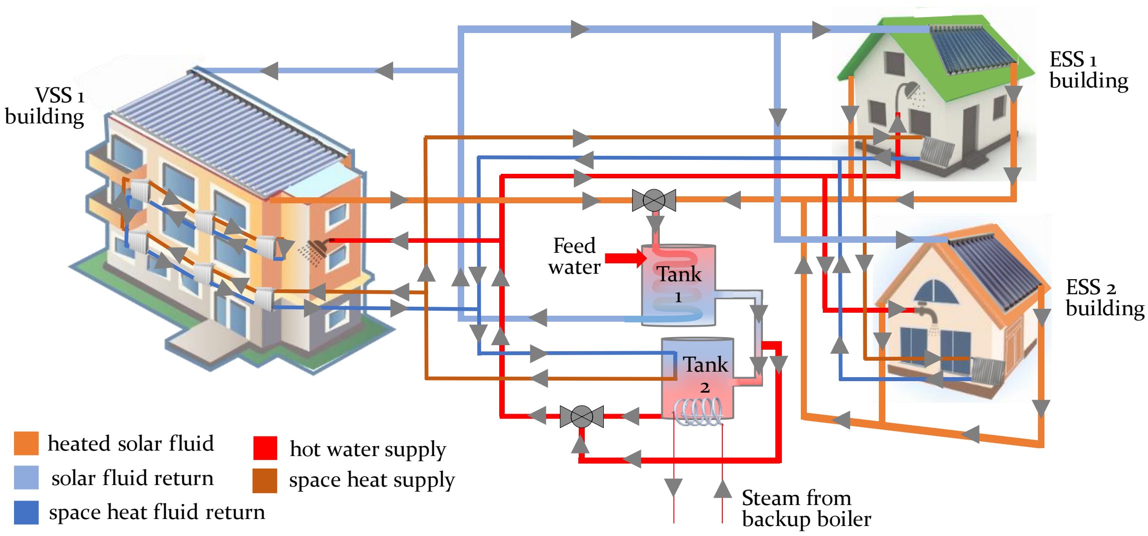

Figure 1: Representation of solar thermal integration for heat utilisation in buildings

2.2 Model approach

The developed model seeks to minimize total heat supplied to the multi-building heat demand network from backup boiler. The objective function for the developed model is shown in Eq(1):

$$\min \Big(\sum_{mp\in MP} \sum_{dp\in DP} \sum_{hp\in hP} \bigwedge_{(mp,dp)\in DPM} \dot{Q}backup^{VSS1}_{mp,dp,hp} + \dot{Q}backup^{ESS1}_{mp,dp,hp} + \dot{Q}backup^{ESS2}_{mp,dp,hp} \Big) \tag{1}$$

where $\dot{Q}backup^{VSS1}_{mp,dp,hp}$, $\dot{Q}backup^{ESS1}_{mp,dp,hp}$ and $\dot{Q}backup^{ESS2}_{mp,dp,hp}$ are the yearly total sum of additional heat from backup utility required for space heating and hot water supply in each of the three buildings. Sets *mp*, *dp* and *hp* represent the monthly, daily and hourly time periods. Monthly and daily time periods are connected through set *DPM* (by logical condition), which stands for the set of pairs of days and months where January has 31 days, February has 29 days and so on (Egieya et al., 2018).

Connections and interactions were established among the various model building blocks which are: solar collectors, heat storage tanks, backup boiler, mixers and splitters as well as the heat network for space heating and hot water supply to the buildings. The integrated system is modelled as a closed-loop superstructure and consists of material and energy balances for the streams flowing across the entire loop.

It is worth stating that variables such as temperatures, flowrates and energy contents of the streams flowing across each unit are dependent on the hourly changing solar irradiation and ambient temperatures while the efficiencies of solar collectors are also considered to be variables which are subject to changes on an hourly basis. Furthermore, the areas of solar thermal collectors and the volume of the fluid in both heat storage tanks are optimization variables with the optimal sizes selected remaining constant throughout the year or in any considered time frame. Since the model involves binary variables, as well as equations that are nonlinear, it is represented as an MINLP formulation, similar to what was presented for the industrial sector scenario by Abikoye et al. (2019). The binary variables ensure that the tank fluid is heated only when the tank temperature is below a stipulated value. In like manner, the temperature of the heat transfer fluid must be lower than the temperature of the return flow to solar collector minus minimum temperature difference (ΔT_{min}).

To reduce the complexity of the model, especially with respect to the nonlinearities, the 24 h duration of a day (hourly time periods) are discretized into smaller number of periods using a clustering rule from previous formulations, and similarly the daily time periods which consist of 29, 30 or 31 days in a month and monthly time periods are discretized to a lower number of periods in a year. The model, which is formulated as a multi-period MINLP problem, has its equations independent of the problem data. Hence, the model can be applied to establish the annual/multiannual potential contribution of solar thermal for any case study in any location.

3. Case study

The integrated solar thermal utilization technique presented in this paper is implemented using heat consumption data obtained from the assessment of the district heating system in Slovenia (MOI, 2017). Three types of reference residential buildings were selected from the report to test the efficacy of the developed model. The buildings are described as: VSS1 (multi-dwelling building), ESS1 (single-family building) and ESS2 (single-family building), see also Figure 1. The data for the case study is shown in Table 1.

The maximum area available for solar collectors (upper bounds) is dependent on the available building. Energy consumption (in kWh/y) is calculated based on available floor area, e.g. for VSS1; space heating amounts to 255,360 kWh/y while hot water use accounts for 44,688 kWh/y, and so on. To represent the various energy consumption data on an hourly basis, 24 h/d are divided into 4 periods (P1-P4): 6 am – 8 am (P1), 9 am – 6 pm (P2), 7 pm – 10 pm (P3), 11 pm – 5 am (P4). Daily time periods (29 – 31 days in a month) are regarded as one period in each month, and the energy consumption is assumed to be the same for each of the days in a month. The energy consumption for space heating and hot water use are allocated on an hourly basis, as shown in Table 2.

Table 1: Baseline scenario for energy consumption in VSS1, ESS1 and ESS2 buildings (MOI, 2017)

Building type	Available roof area (m^2)	Available floor area (m^2)	Energy consumption kWh/(m^2y)	
			Space heating	Hot water use
VSS1	470	1596	160	28
ESS1	107	147	230	27
ESS2	107	234	190	27

Table 2: Allocation of energy consumption on an hourly basis for the three buildings (in %)

Building type	VSS1		ESS1		ESS2	
	Space heating[1)]	Hot water use[2)]	Space heating[3)]	Hot water use[4)]	Space heating[5)]	Hot water use[6)]
January	25	11.25	20	11.25	31	9.25
February	20	9.17	15	8.75	20	9.08
March	10	9.58	10	9.58	10	7.92
April	5	8.75	7	8.75	2	8.58
May	/	8.08	/	8	/	8.08
June	/	7.92	/	7.67	/	7.92
July	/	3.33	/	5.17	/	6.75
August	/	3.75	/	3.42	/	7.08
September	/	8.75	/	8.75	/	9.17
October	5	9.58	7	8.58	2	8.92
November	15	9.58	21	9.67	10	8.33
December	20	10.25	20	10.42	25	8.92

[1)] 30 % in P1, 30 % in P2, 40 % in P3 and 0 in P4, [2)] 30 % in P1, 25 % in P2, 35 % in P3 and 10 % in P4,
[3)] 10 % in P1, 30 % in P2, 50 % in P3 and 10 % in P4, [4)] 10 % in P1, 35 % in P2, 40 % in P3 and 15 % in P4,
[5)] 35 % in P1, 40 % in P2, 25 % in P3 and 0 in P4, [6)] 35 % in P1, 45 % in P2, 20 % in P3 and 0 in P4

Hourly solar irradiation and ambient temperature data were considered for the selected location near Maribor, Slovenia (coordinates: Latitude 46.552 N, Longitude 15.676 E, 267 m above the sea level) and were obtained from EC JRC PVGIS project database (EC JRC PVGIS, 2017). With the availability of information on hourly changes in meteorological conditions and that of the hourly changes in total heat demand by each of the building (see Tables 1 and 2), the design and optimisation task is then to minimise heat supply from the backup utility.
Similarly, as the data for heat demand in each of the building, the model is discretised into the same four periods of a day (P1-P4) while the 29 – 31 days of the month were discretized into one period. Two scenarios were further considered due to their peculiarities: i) scenario for winter months which includes the months November – February, and ii) scenario for summer months which is made up of the months June – September. Thus, 4 hourly, 1 daily and 4 monthly periods were considered in each of the scenarios. Since the models are highly nonlinear, upper bounds were set on the flowrates (100 t/h), heat load (1,000 kW), volume of fluid in the storage tanks (300 m^3), areas of solar collectors for each building (see available roof area in Table 1) and temperature across the loops (99 °C). The inlet temperature of feed water to Tank 1 is assumed to be 20 °C, ΔT_{min} is 10 °C, the minimum temperature for hot water use is 55 °C, while temperature for space heating in radiator system is 70 °C. The outlet temperature of radiators is assumed to be 20 °C lower (e.g. 70/50 °C). For simplicity, the temperature of backup utility to Tank 2 is fixed at 120 °C, while the temperature of fluid returning to the backup boiler is set as a variable. For energy balance calculations, a reference temperature of 20 °C is selected.
The developed models are solved using SBB solver in GAMS environment (GAMS Development Corporation, 2019). They consist of approximately 3,300 single equations, 3,100 single variables, and 16 binary variables. The models were solved on a personal computer with Intel® Core™ i7-8700K CPU @ 3.70 GHz processor, 64 GB of RAM and solution to the problems was obtained in few seconds with 5 % optimality gap.

3.1 Results of the first scenario (winter months)

The average values obtained for variables, such as flowrates, temperatures and changes in heat load for the first scenario considering four winter months are shown in Table 3.
The optimal areas of solar collectors selected by the model are 256.79 m^2 for VSS1, 107 m^2 for ESS1 and 107 m^2 for ESS2, while the upper bound volume of 300 m^3 is the optimal values chosen for the two storage tanks. The solution indicates using solar thermal for hot water only, while in the case of space heating, the backup utility is required. Overall, 177.28 kWh/d on average is provided by solar energy, while 2,217.67 kWh/d is required to be provided by the backup utility. The is because the temperature achieved through solar heating of Tank 1 in the winter months considered is too low (55.67 – 56.41 °C) to be used for space heating where a minimum temperature of 70 °C is required. The energy required for hot water use is provided from two sources, which are the feed water (3.02 kWh/d on average) and solar collectors (177.28 kWh/d on average) in period P2. The quantities of energy provided by solar thermal are: November (129.23 kWh/d), December (257.35 kWh/d), January (210.21 kWh/d) and February (112.32 kWh/d). In winter months therefore 7.40 % of the required energy is provided by solar thermal.

Table 3: Average values of variables for the scenario considering four winter months

	Flowrate (t/d)	Temperature (°C)	Change in heat load (kWh/d)
Collector, VSS1	28.17	66.93 / 83.68	96.70
Collector, ESS1	11.74	66.93 / 83.68	40.29
Collector, ESS2	11.74	66.93 / 83.68	40.29
Feed water	4.311	20.60	3.02
Tank 1	55.96	55.67 – 56.41*	/
Tank 2	99.13	92.57 – 99.00*	/
Space heat, VSS1	72.81	81.87 / 61.87	1,689.29
Space heat, ESS1	9.14	80.19 / 60.19	211.87
Space heat, ESS2	13.64	81.87 / 61.87	316.28
Hot water, VSS1	3.55	56.10	148.57
Hot water, ESS1	0.31	56.10	13.13
Hot water, ESS2	0.44	56.10	18.60
Backup boiler	3.54	109 / 120	2,217.67

* temperature in the storage tank

3.2 Results of the second scenario (summer months)

The average values obtained for flowrates, temperatures and heat loads for the second scenario, which considers four summer months are shown in Table 4. The optimal areas of solar collectors considering four summer months in the three-building types are 3.69 m^2 for VSS1, 2.42 m^2 for ESS1 and 27.43 m^2 for ESS2, while the volume of fluid in Tank 1 is 300 m^3. It should be noted that the areas selected for solar collectors in the second scenario are smaller due to comparatively higher solar irradiation and less demand for heat in the summer months. The model suggests no use of backup utility and all the requirements for hot water use are satisfied by solar thermal (111.56 kWh/d on average) and feed water (0.27 kWh/d on average). The energy supplied by the solar collectors is provided in periods P1 and P2. The quantity of energy supplied by the collectors in each of the summer months for P1 and P2 are:18.22 and 83.29 kWh/d in June, 23.72 and 102.05 kWh/d in July, 17.76 and 98.35 kWh/d in August, 17.29 and 85.54 kWh/d in September. In this second scenario, the total energy required for hot water use across the summer months is satisfied by solar thermal.

Table 4: Average values of variables for the scenario considering four summer months

	Flowrate (t/d)	Temperature (°C)	Change in heat load (kWh/d)
Collector, VSS1	0.24	65.51 / 95.58	12.29
Collector, ESS1	5.99	65.51 / 95.58	8.04
Collector, ESS2	0.19	65.51 / 95.58	91.23
Feed water	2.74	20.08	0.27
Tank 1	9.16	55 – 65.50*	/
Hot water, VSS1	2.15	55.17	87.47
Hot water, ESS1	0.20	55.17	8.20
Hot water, ESS2	0.40	55.17	16.14

* temperature in the storage tank

4. Conclusions

In this paper, a new simultaneous multi-period MINLP approach for the design and optimisation of solar heat network in a cluster of buildings has been presented. The proposed method considers hourly-based values of meteorological parameters such as solar irradiation and ambient temperature and also enables optimization of the dynamic behaviour of the solar heat supply and utilization based on hourly, daily and monthly time periods. The method is demonstrated on a case study in Slovenia involving a cluster of three different types of buildings where the provision of hot water and space heat by solar thermal are demonstrated for winter and summer months. However, the method could be applied to a different case study in any geographical location because the equations surrounding the model building blocks are developed independently of the data.

The results obtained show that the maximum attainable heat from solar is 7.4 % of the total heat required, and collector sizes of 256.79 m^2 for VSS1 and 107 m^2 for both ESS1 and ESS2 are selected. Though solar heat utilization for hot water is completely satisfied in this period, space heating is constrained because the maximum temperature level (55.67 – 56.41 °C) of solar fluid in this period of the year is lower than the minimum temperature required by radiators for space heating. Hence solar energy is used only as a pre-heating source of heat in the winter months. On the contrary, in summer months all the demand for domestic heating is satisfied

by solar thermal with the collector areas of 3.69 m^2 for VSS1, 2.42 m^2 for ESS1 and 27.43 m^2 for ESS2. It should be noted that the selected collector areas in the two scenarios are far less than the available space on the rooftops for the three-building types considered.
Nevertheless, the potentials and the total operating time of solar thermal collectors can be further extended by combining other clean energy/energy efficiency technologies with the integrated solar thermal network. The possibility of incorporating heat pump (with or without the combination of heat and power cogeneration unit) and studying the effects of heat losses on the total attainable solar thermal for utilization in buildings during long-term storage will be investigated in future works.

Acknowledgements

The authors are grateful for the travel supports received from the Research Office of the University of Cape Town (UCT), the South African National Research Foundation under Grant Number 105780, the Slovenian Research Agency (research core funding No. P2-0412 and P2-0032 and projects J7-1816 and L2-7633) and the Erasmus+ programme of the European Union. The authors would also like to acknowledge Klavdija Zirngast from the University of Maribor for her helpful discussions and contributions.

References

Abikoye B., Čuček L., Isafiade A.J., Kravanja Z., 2019, Integrated design for direct and indirect solar thermal utilization in industrial operations, Energy, 182, 381-396.
Davidson J.H., Quinnell J., Burch J., Zondag H.A., de Boer R., Finck C., Cuypers R., Cabeza L.F., Heinz A., Jahnig D., Furbo S., Bertsch F., 2013, Development of Space Heating and Domestic Hot Water Systems with Compact Thermal Energy Storage, Compact Thermal Energy Storage: Material Development for System Integration <task5.iea-shc.org/data/sites/1/publications/T4224-B2--Development-of-Space-Heating-and-Domestic-Hot-Water-Systems-with-Compact-Thermal-Energy-Storage.pdf> accessed 5.7.2019.
Dehghan A.A., Barzegar A., 2011, Thermal performance behaviour of a domestic hot water solar storage tank during consumption operation. Energy Conversion and Management, 52, 468-476.
Egieya J.M., Čuček L., Zirngast K., Isafiade A.J., Pahor B., Kravanja Z., 2018, Biogas Supply Chain Optimization Considering Different Multi-Period Scenarios, Chemical Engineering Transactions, 70, 985-990.
Energy Information Administration (EIA), 2013, Independent statistics on energy use in homes <www.eia.gov/energyexplained/index.php?page=us_energy_homes> accessed 24.11.2018.
European Commission Joint Research Centre Photovoltaic Geographical Information System (EC JRC PVGIS), 2017, PVGIS tools <re.jrc.ec.europa.eu/pvg_tools/en/tools.html> accessed: 8.8.2018.
European Renewable Energy Research Centres (EUREC) Agency, 2013, Energy technologies and innovation in a future European energy policy <eurec.be/en/upload/docs/pdf/EUREC-%20Input%20for%20the%20EC%20Communication.pdf> accessed 27.6.2019.
Fuentes E., Arce L., Salom J., 2018, A review of domestic hot water consumption profiles for application in systems and buildings energy performance analysis. Renewable and Sustainable Energy Reviews, 81, 1530-1547.
GAMS Development Corporation, 2019, <www.gams.com> accessed: 5.7.2019.
Kee S.Y., Munusamy Y., Ong K.S., 2018, Review of solar water heaters incorporating solid-liquid organic phase change materials as thermal storage. Applied Thermal Engineering, 131, 455-471.
Le Quéré C., Andrew R.M., Canadell J.G., Sitch S., Korsbakken J.I., Peters G.P., Manning A.C., Boden T.A., Tans P.P., Houghton R. A., Keeling R. F., Alin S., Andrews O. D., Anthoni P., Barbero L., Bopp L., Chevallier F., Chini L.P., Ciais P., Currie K., Delire C., Doney S.C., Friedlingstein P., Gkritzalis T., Harris I., Hauck J., Haverd V., Hoppema M., Klein Goldewijk K., Jain A.K., Kato E., Körtzinger A., Landschützer P., Lefèvre N., Lenton A., Lienert S., Lombardozzi D., Melton J.R., Metzl N., Millero F., Monteiro P.M.S., Munro D.R., Nabel J.E.M.S., Nakaoka S.I., O'Brien K., Olsen A., Omar A.M., Ono T., Pierrot D., Poulter B., Rödenbeck C., Salisbury J., Schuster U., Schwinger J., Séférian R., Skjelvan I., Stocker B.D., Sutton A.J., Takahashi T., Tian H., Tilbrook B., van der Laan-Luijkx I.T., van der Werf G.R., Viovy N., Walker A.P., Wiltshire A.J., Zaehle S., 2016, Global Carbon Budget 2016, Earth System Science Data, 8, 605-649.
Saini P., Patil D.V., Powar S., 2017, Review on integration of solar air heaters with thermal energy storage. Energy, Environment, and Sustainability, 163-186.
Republic of Slovenia Ministry of Infrastructure (MOI), 2017, Expert basis for a comprehensive assessment of options for cogeneration and district heating, Final report <ec.europa.eu/energy/sites/ener/files/documents/strokovne_podlage_porocilo-_24_en.pdf> accessed: 6.9.2018.
United Nations Environment Programme (UNEP), 2014, Integrating solar thermal in buildings – Quick guide for architects and builders <www.estif.org/fileadmin/estif/content/publications/downloads/unep_report_final_v04_lowres.pdf> accessed 22.11.2018.