International Conference on Applied Energy 2021
Nov. 29 - Dec. 5, 2021, Thailand/Virtual
Paper ID: 0480

Techno-economic analysis of hybrid thermal energy storage in energy industries

Pouriya H Niknam[1*],Yulong Ding[1], Adriano Sciacovelli[1]

1* School of Chemical Engineering, Birmingham Centre for Energy Storage, University of Birmingham, UK,

p.niknam@bham.ac.uk

ABSTRACT

Thermal energy storage (TES) plays a crucial role in waste heat recovery and decarbonisation of the industrial sector and energy efficiency improvement. The combination of two energy storage technologies makes TES a promising asset for managing different types of energy in a single system; however, such an opportunity has not received attention so far. To overcome the traditional view of TES based on a single approach only, this study investigates the techno-economic value of using hybrid TES (HTES) as a multi-tech energy storage asset for the provision of energy streams either in low or high energy density for the industrial applications. The system is envisioned to consist of sub-sections which to provide fast-response TES as well as longer-duration TES. The selected case study is a hybrid water-latent heat system. The former accept steam while the latter can support the former and optionally receive energy from an additional source. The study discusses the technical characteristics and the interaction of the compartments. Compared to a conventional TES, the proposed HTES provides a relevant 20-30% increase in overall storage capacity based on fixed equipment size. The economic analysis revealed that the potential reduction in investment cost and O&M cost are found between 6 to 20%, making this technology an appealing solution for waste heat recovery.

Keywords: waste heat recovery, techno-economic analysis, Thermal energy storage, thermal battery, Hybrid energy storage.

1. INTRODUCTION

Industries take advantage of the progress made in recent years in the development of waste heat recovery methods, and one of the emerging ones is thermal energy storage (TES) which has an increasing trend in the research to be integrated into the various industrial application. TES has the potential to enhance energy management and support taking more aggressive steps toward decarbonisation. Thermal energy can be stored as sensible heat by changing the temperature, latent heat by changing the phase, or chemical heat by reversible reactions.

The wide range of TES applications turns to motivation for the researcher to enhance the performance and flexibility of the system. One potential solution is hybridisation and simultaneously taking advantage of multiple technologies. The TES hybridisation concept was proposed by Zauner et al., who formulated a hybrid sensible-latent heat with the shell and tube heat exchanger configuration. The PCM was put within the tube, and the heat transfer fluid flowed through the shell and tube configuration was mentioned as the limit of PCM share [1]. Similar studies performed by Geissbühler et al. and Zanganeh et al. provided technical proof for industrial applications of HTES. They conducted experiments evaluating the HTES performance in high temperatures based on a packed bed with an encapsulated PCM with a limited percentage of the total volume due to construction limits [2,3]. Dusek et al. evaluated a new combination of technologies, including Ruth's steam storage and PCM. The study was based on a one-dimensional model and showed that the steam capacity increased by 29% [4]. A more in-depth numerical analysis was performed by Pernsteiner et al. using a two-dimensional model discussing the thermal coupling of the sub-sections of the hybrid steam-PCM system [5]. Hoffman et al. extended the study of Dusek et al. by modelling various mechanical arrangements for the sub-sections within the hybrid TES. The research efficiently attempted to optimise the design, but economic aspects were limited to the cost of investment [6]. In a comparative study, Beck et al. evaluated various energy storage technologies, including steam storage, latent heat, PCM and concrete, discussing the energy price for individual and dual-technology solutions. The study focused only on the investment cost for the TES neglecting the impact on plant design and O&M cost [7]. Each of the above carried on research on a specific case study with the concept of hybrid TES but did not deeply examine the economic benefits of the hybridisation to the industrial end-users. The research gap is a more comprehensive high-level assessment to extract representative data for technical and economic benefits.

According to Fig. 1, the present study aimed to discuss how the hybrid configuration gives the industries additional economic benefits by saving energy and reducing the cost of investment. The hybridisation concept potentially reduces the cost of investment for storing the energy. Moreover, the enhanced flexibility of the HTES in accepting multi-energy types will increase the return of investment by reducing the cost of operation. The present study aimed to represent qualitative data by techno-economic analysis. Integration of HTES as an emerging technology is more likely to be adopted by the industries when they have certainty regarding technical superiority and long-term profitability.

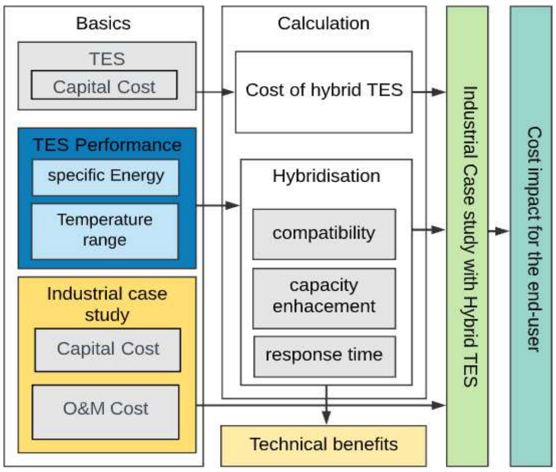

Fig. 1. Structure of the study

2. METHODOLOGY

The industrial case study includes a gas boiler fueled by natural and a Hybrid TES; both support an industrial process with steam demand. The case-study boiler is determined to provide low-pressure steam for a process case with a demand of 52 GWh per year and an approximately 7 MW capacity.

The boiler detail is used for the economic assessment while the HTES needs to be technically implemented, and then the outputs are used for the economic analysis.
The hybrid section includes primary and secondary TES subsections. Each can operate independently whilst internally supporting the other by transferring the heat

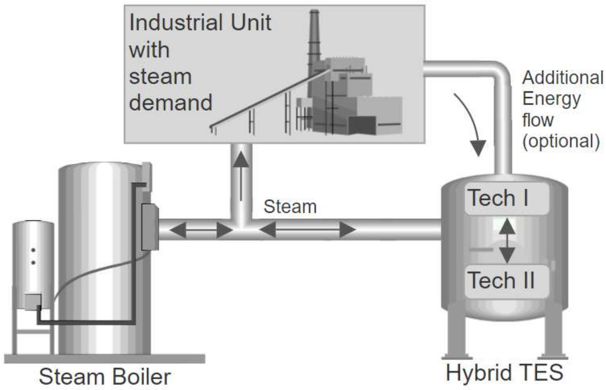

Fig. 2. The outline of industrial application for hybrid TES

through the interface, contributing to overall efficiency enhancement. The primary TES is a steam storage system composed of a cylindrical tank of water heated by steam injection reaching the saturation condition. On peak stem demand, the discharge valve opens, and water is flashed to steam. The water and steam proportions are variable, and the system is working in the approximate range of 100-400°C. Modelling of HTES provides knowledge on the energy capacity of both subsections and the hybrid one. The primary subsection model determines phase change in the water-steam equilibrium state; however, the total volume is constant. The mass balance in the liquid and vapour zones are based on the phase change rate:

$$\frac{dm_L}{dt} = \dot{m}_{L,in} - \dot{m}_{L,out} + \dot{m}_{cond} - \dot{m}_{vap} \quad (1)$$

$$\frac{dm_V}{dt} = \dot{m}_{V,in} - \dot{m}_{V,out} - \dot{m}_{cond} + \dot{m}_{vap} \quad (2)$$

in which $\dot{m}_{i,in}$ and $\dot{m}_{i,out}$ are the inlet and outlet of liquid (L) or vapour (V) phase mass flow rate. The following terms represent condensing and evaporating rates.

The water can heat or cool depending on the heat transfer between the tank and the environment. Eqs. 3 & 4 are the energy balance in the liquid and vapour zones, Respectively.

$$M_L \frac{du_L}{dt} + \frac{dM_L}{dt} u_L = \phi_{L,in} - \phi_{L,out} + \phi_{cond} - \phi_{evap} + Q_L \quad (3)$$

$$M_V \frac{du_V}{dt} + \frac{dM_V}{dt} u_V = \phi_{V,in} - \phi_{V,out} - \phi_{cond} + \phi_{evap} + Q_V \quad (4)$$

in which ϕ_{in}, ϕ_{out}, ϕ_{cond}, ϕ_{evap} are inlet, outlet, condensation and evaporation energy flow rates. The heat transfer between liquid or gas and the environment are Q_L and Q_V. The PCM part is implemented separately, and the link between steam storage as TES I and the PCM as TES II is determined through conduction heat from the tank surface. The sensible heat within the PCM part is defined as Eq.5 and Eq. 6:

$$Q_1 = \frac{dm_1}{dt} C_p (T_{pc} - T_1) - m_1 C_p \frac{dT_1}{dt} \quad (5)$$

$$Q_2 = \frac{dm_2}{dt} C_p (T_{pc} - T_2) - m_2 C_p \frac{dT_2}{dt} \quad (6)$$

in which the Q_1 is the heat flow to phase one (liquid at the charging phase) through the steam tank surface and Q_2 is for phase 2 (solid at the charging phase) located in series after phase 1. Meanwhile, m_i and T_i represented the corresponding mass and temperature. Further details on the joint operation of HTES subsections can be found in the related study developed by Dusek et al. [4].

The cost associated with the industrial plant benefiting the HTES can be assessed as generation cost (GC), accounting for the lifetime fuel costs and other operating costs as well as the capital cost.

$$GC = CAPEX + TL\ (O\&M_{non-fuel} + FC) \quad (7)$$

in which CAPEX is the cost of investment mainly for the equipment. TL is the technology lifetime which is commonly 25 years for the boiler systems. The O&M and FC are the operating and maintenance cost and fuel cost. CAPEX is calculated by the cost curves for the boiler as a function of capacity [8]. The average unit price for the TES subsections is estimated based on literature within 40 to 80 €/kWh for the steam storage and about 20€/kWh for the PCM systems. The results are updated for the year 2020 CEPCI index. Moreover, O&M costs are estimated based on the literature data as a function of the CAPEX value. The annual O&M cost is within 1 to 6% of the CAPEX, while the fuel cost (FC) highly depends on the gas price, roughly within 4 to 20% of the CAPEX. However, the exact fuel cost is estimated based on 7500 yearly operating hours and the EU average price for non-household consumers, which was 0.0279 €/kWh in 2020.

Table 1-Assumptions for the cost calculations

Parameter	Range	mean	Ref.
Tech 1 (SS) specific energy price [€/kWh]	[20 140]	40	[9, 10, 11, 12, 13, 14]
Tech 2 (PCM) specific energy price [€/kWh]	[10-50]	15	[15, 16]
$\frac{\text{Boiler O\&M cost}}{\text{CAPEX}}$ [%]	[4-21]	4.5	[14, 17, 18, 19, 20, 21]
Boiler fuel cost [c€/kWh]		2.79	[22]
Natural gas net calorific value (NCV) [MJ/m3]	[34.2-37.2]	35.3	[23]
NG boiler Lifetime [yr]	-	25	[14]
TES Lifetime [yr]	[25-40]	25	[14]

3. RESULTS AND DISCUSSION

The state of charge of the HTES over the whole duration of the charging/discharging is illustrated in Figure 3. Furthermore, the result also presents the fraction of energy stored in steam storage (SS) and PCM. The system allows different response times because the steam storage is a fast response compared to the PCM, which provides a longer duration storing the heat. The HTES performance includes the charging phase, idle period, and discharging time, shown in Fig. 3. The SS subsection has a dominant role over PCM in energy capacity. The PCM part supports the steam storage section in the charging phase. The difference is more highlighted in the discharging step when the SS delivers the energy quickly whilst the PCM fulfils the energy demand for a more extended period.

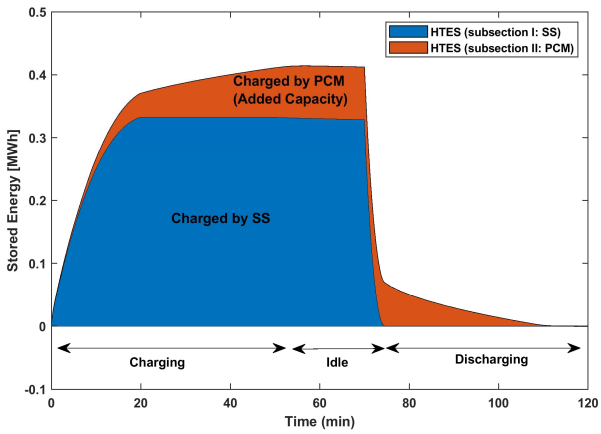

Fig. 3. State of charge of the HTES

The above results related to employment if the PCM as the secondary TES in the hybrid configuration with the volumetric share of 5%. As shown in Fig. 4, The corresponding energy assessed energy capacity enhancement is found to be more than 27% in the same storage volume.

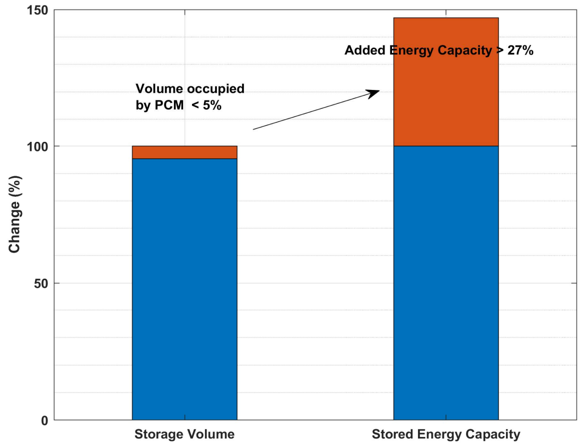

Fig. 4. HTES capacity compared with conventional storage

A sensitivity analysis is performed to investigate the role of the PCM subsection in the HTES. The ratio of HTES energy capacity to the TES is assessed in different PCM volumetric allocations and types. In this analysis, the remaining parameters, including the radius of steam storage (R_1) are kept unchanged. In the cylindrical configuration, the PCM share can be represented as a volumetric fraction or the ratio of total radius (R_2) to the base design. As shown in Fig. 5, by adding PCM to the steam storage, the capacity can be increased up to 50%. The PCM share of up to 30% of total volume positively affects energy capacity enhancement. Conversely, a higher PCM share reduces the overall energy capacity. In that case, the PCM response time will not be aligned with the steam storage; thus, the large part of the PCM doesn't involve the phase change; conversely, it performs as a sink which potentially reduces the capacity. So the optimal HTES configuration benefits from the PCM contribution when it is fully involved in the phase-change.

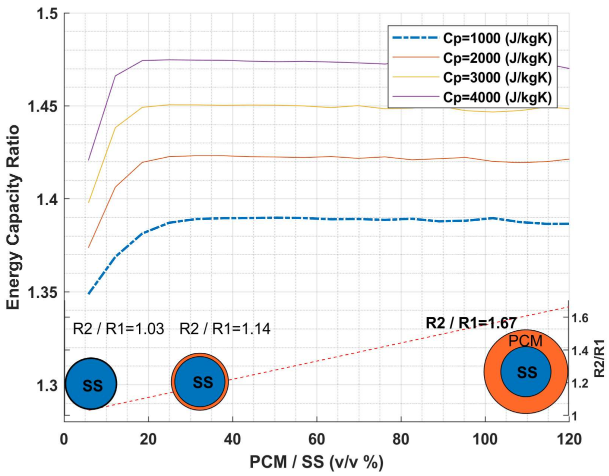

Fig. 5. Energy enhancement by various PCM proportions

Either the conventional steam storage or the HTES is capable of storing the surplus steam produced by the boiler at times of low demand for subsequent release to supplement the output of the boiler at times of high demand. The industrial steam demand usually fluctuates over time, and the process energy efficiency highly depends on the alignment of the boiler and the process and how the process benefits from energy recovery technologies like energy storage. A sample steam demand profile from food industries is selected [24]. There are several up and down peaks over a 2-hour time window. The boiler design capacity can be adjusted to the maximum load or lower levels which are marked as A, B, C and D in Fig 6. For example, the difference between steam demand and the supplied steam from the boiler is highlighted for the reduced capacity B.

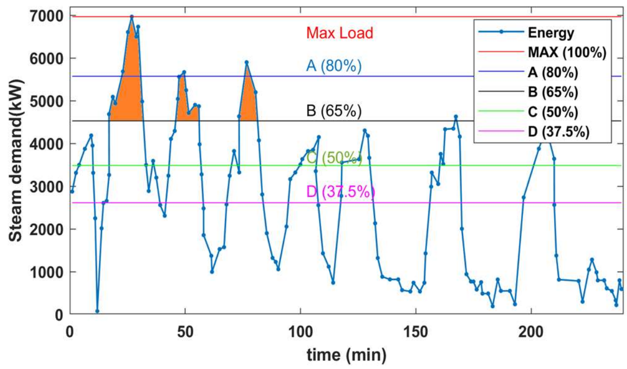

Fig. 6. Steam demand profile (data from [24])

The HTES supports the boiler with lower capacity, and the steam is instantaneously released from storage to meet sudden changes in demand. Any inconsistency between boiler and steam storage capacity contributes to the failure of steam supply. According to case D, the optimum capacity is found around 37.5% of the maximum level, where charging and discharging are equal (Fig 7). The boiler is expected to operate steadily at this capacity while the peaks in steam demand are fulfilled by the TES/HTES.

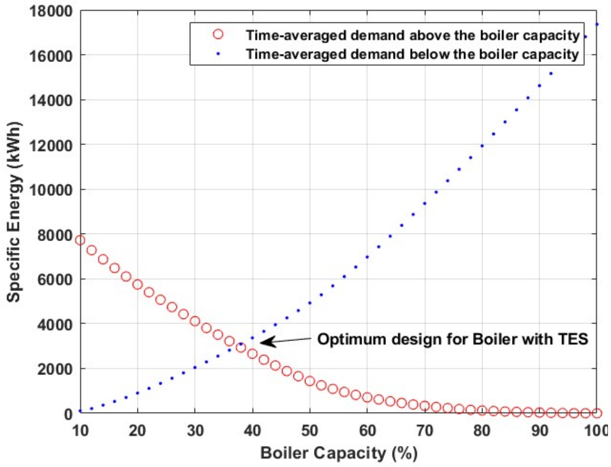

Fig. 7. Balance of load above and below the boiler capacity

By using the optimal capacity of the boiler, further analysis is assessed for the configuration of HTES. Four TES configurations are defined which can support the reduced-capacity boiler fulfilling the maximum capacity.
i) Steam storage (SS) only;
ii) SS jointly working with PCM (energy duty 80%-20%);
iii) SS jointly working with PCM (energy duty 50-50;
iv) SS with PCM (50-50), where 10% of HTES energy input is provided from an additional energy source.

The generation cost is assessed for all cases and compared with the base design in which the boiler fulfils the total steam demand, which is shown in Fig. 8. Since the fuel cost has a dominant share in GC, the CAPEX is separately compared to reveal the impact of TES & HTES in the investment cost.

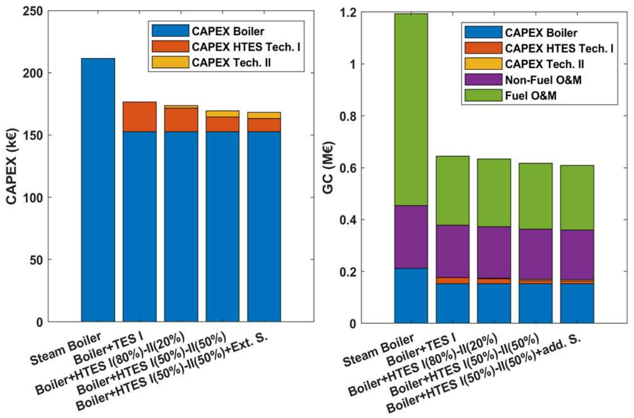

Fig. 8. Generation cost for various scenarios

The financial impact for the end-user is assessed by the estimation of the generation cost of the plant lifetime. All capital, non-fuel O&M, and fuel costs are notably reduced by 6%, 10% when TES and HTES are implemented. These values for O&M are 16.5% and 21% for TES and HTES, respectively. Moreover, the effect of an additional source (which provides 10% of HTES) for charging HTES is 1% in the industrial plant generation cost.

4. CONCLUSIONS

In this paper, we proposed the use of Hybrid TES to enhance the performance of an energy storage system and reduce the cost. Three configurations were studied: a steam boiler, steam boiler with steam storage, steam boiler with hybrid TES. The results indicate that optimal hybrid configuration brings substantial performance improvements: and the energy capacity increases by about 27% when HTES benefits from secondary TES technology. The positive contribution of PCM in HTES performance is technically limited to PCM allocation of up to 30%. The internal design of HTES was evaluated to reveal how different combinations bring cost savings to the industrial end-user. The economic analysis was carried out by estimation of investment cost and O&M cost. The employment of HTES noticeably reduces both the investment and O&M costs. Therefore, the long-term generation cost is reduced between 6 to 20% when both boiler and HTES are in service. Considering the cost impact and efficiency improvement, the HTES has more chance to be accepted by the industries.

ACKNOWLEDGEMENTS

Funding: This work was supported by the European Union's Horizon 2020 research and innovation programme [grant number 847097; SO WHAT project].

REFERENCE

[1] Zauner, C., Hengstberger, F., Mörzinger, B., Hofmann, R., & Walter, H. Experimental characterization and simulation of a hybrid sensible-latent heat storage. Appl. energy. 2017; 189:506-19.
[2] Geissbühler, L., Kolman, M., Zanganeh, G., Haselbacher, A., & Steinfeld, A. Analysis of industrial-scale high-temperature combined sensible/latent thermal energy storage. Appl. Therm. Eng. 2016; 101:657-68.
[3] Zanganeh, G., Khanna, R., Walser, C., Pedretti, A., Haselbacher, A., & Steinfeld, A. Experimental and numerical investigation of combined sensible–latent heat for thermal energy storage at 575 C and above. Sol. Energy. 2015; 114:77-90.

[4] Dusek S, Hofmann R. A hybrid energy storage concept for future application in industrial processes. Therm. Sci. 2018;22(5):2235-42.
[5] Pernsteiner, D., Kasper, L., Schirrer, A., Hofmann, R., & Jakubek, S. Co-simulation methodology of a hybrid latent-heat thermal energy storage unit. Appl. Therm. Eng. 2020; 178:115495.
[6] Hofmann, R., Dusek, S., Gruber, S., & Drexler-Schmid, G. Design optimisation of a hybrid steam-PCM thermal energy storage for industrial applications. Energies. 2019; 12(5):898.
[7] Beck A, Sevault A, Drexler-Schmid G, Schöny M, Kauko H. Optimal Selection of Thermal Energy Storage Technology for Fossil-Free Steam Production in the Processing Industry. Appl. Sci. 2021; 11(3):1063.
[8] Sinnott R, Towler G. Chemical engineering design: SI Edition. Butterworth-Heinemann; 2019 May 26.
[9] Technology and case studies factsheets, Ref. Ares(2019)2377231 - 03/04/2019, https://www.magnitude-project.eu/wp-content/uploads/2019/07/MAGNITUDE_D1.2_EIFER_Final_Submitted.pdf (last visit on 17 September 2021)
[10] Gibb D, Seitz A, Johnson M, Romani J, Gasia J, Gabeza LF, Gurtner R, Vandersickel A. Applications Of Thermal Energy Storage In The Energy Transition-Benchmarks and developments. Lehrstuhl für Energiesysteme; 2018.
[11] Kauko H, Sevault A, Beck A., Drexler-Schmid G., Thermal storage for improved utilisation of renewable energy in steam production, https://app.cristin.no/results/show.jsf?id=1744103 (last visit on September 17, 2021)
[12] Mikkelson D, Frick K, Bragg-Sitton S, Doster JM. Phenomenon Identification and Ranking Table Development for Future Application Figure-of-Merit Studies on Thermal Energy Storage Integrations with Light Water Reactors. Nuclear Technology. 2021 Aug 4:1-8.
[13] Buseth ER. Renewable Energy in Longyearbyen (Master's thesis, NTNU). https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2778263/no.ntnu:inspera:54193643:20970718.pdf (last visit on September 17, 2021)
[14] Abdallas Chikri, Y. Hybrid boiler systems in the Dutch industry: A techno-economic analysis of the potential of hybrid boiler systems to cost-effectively decarbonise steam generation in the Dutch industry. 2020.
[15] Radcliffe J, Li Y. Thermal energy storage in Scotland, 2015., https://climatexchange.org.uk/media/1393/thermal_energy_storage_in_scotland.pdf. (last visit on September 17, 2021)
[16] Hauer, A. Storage Technology Issues and Opportunities, International Low-Carbon Energy Technology Platform. In Proceedings of the Strategic and Cross-Cutting Workshop "Energy Storage—Issues and Opportunities", Paris, France, 15 February 2011.
[17] Yeh S, Rubin ES. A centurial history of technological change and learning curves for pulverised coal-fired utility boilers. Energy. 2007 Oct 1;32(10):1996-2005.
[18] Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables) https://ec.europa.eu/energy/sites/ener/files/documents/mapping-hc-final_report-wp2.pdf (last visit on September 17, 2021)
[19] Beltran H. Modern portfolio theory applied to electricity generation planning. Urbana-Champaigne: University of Illinois. 2009.
[20] EIA U. Capital Cost Estimates for Utility Scale Electricity Generating Plants; US Department of Energy. Energy Information Administration: Washington, DC, USA. 2016.
[21] Lyons S, Durusut E, Moore I. Industrial Fuel Switching Market Engagement Study. Element Energy, Cambridge. 2018.
[22] Natural gas price statistics, https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Natural_gas_price_statistics#Natural_gas_prices_for_non-household_consumers. (last visit on September 17, 2021)
[23] International Energy Agency, Key World Energy Statistics. 2021: Paris. https://iea.blob.core.windows.net/assets/52f66a88-0b63-4ad2-94a5-29d36e864b82/KeyWorldEnergyStatistics2021.pdf (last visit on September 17, 2021)
[24] Hechelmann, R. H., Seevers, J. P., Otte, A., Sponer, J., & Stark, M. Renewable Energy Integration for Steam Supply of Industrial Processes-A Food Processing Case Study. Energies. 2020;13(10):2532.

