CHEMICAL ENGINEERING TRANSACTIONS

VOL. 88, 2021

A publication of AIDIC

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

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

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

DOI: 10.3303/CET2188097

Cost Analysis for CO_2 Reduction Pathways

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It has been widely acknowledged that addressing the issue of climate change should focus on reducing, and ideally eliminating, the influx of CO_2 to the atmosphere. This has led to the emergence of various CO_2-reducing technologies, which differ in their economic and environmental performances. Considering only one side of the problem may be misleading, so this work introduces a novel high-level cost analysis methodology which assesses the different CO_2 reduction options based on CO_2 marginal abatement cost - MAC (an indicator that integrates environmental and economic performances). The study contributes to the existing literature by accounting for the impact of the temporal variations in power demand and renewable energy sources on the MAC of the considered options. The proposed approach is demonstrated through an analysis that explores integrated pathways for CO_2 reduction through CCUS technologies and renewable energy technologies. Energy storage is considered for the intermittent renewable energy options. The results for the different scenarios are combined on a Mini-MAC curve, a recently developed cost analysis tool for planning CO_2 reduction pathways, in which significant insights on the economics of the CO_2 reduction are demonstrated and analyzed.

1. Introduction

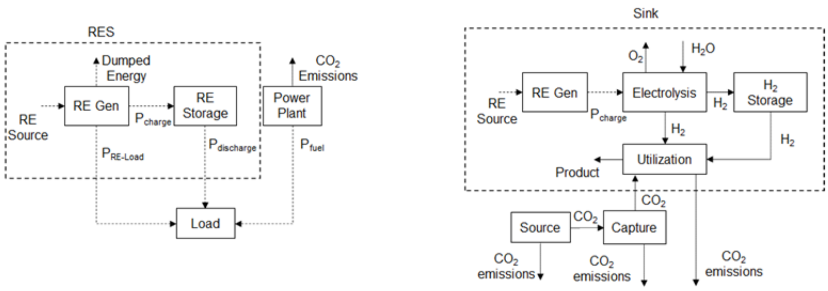
Climate change is a major challenge that requires urgent actions towards reducing greenhouse gas emissions to limit the rise in global temperature. This would require reducing the global CO_2 emissions to net zero (IEA, 2021), which in turn requires a wide scale implementation of CO_2 reducing technologies. Different options exist for CO_2 reduction among which renewable energy systems (RES) and CO_2 capture, utilization, and storage (CCUS) are considered as key pillars (IEA, 2021). The performance of such pathways is assessed from the environmental point of view through life cycle assessment analyses - LCAs (Thonemann and Pizzol, 2019) or from a technological/economic perspective through technoeconomic analyses - TEAs (Hepburn et al., 2019). It is important to consider both the techno-economic and environmental performances when planning for CO_2 reduction in order to avoid falling in common pitfalls of prioritizing options that perform well in one criterion but fail in another (example: profitable CO_2 utilization pathways that produce more CO_2 as secondary emissions than they utilize). One method of integrating LCAs and TEAs is by considering the marginal abatement cost (MAC) of CO_2 reduction, which is the cost associated with a certain life cycle CO_2 reduction level (Zimmermann et al., 2020). Optimization approaches have been developed to guide a detailed implementation of cost-optimal CO_2 reduction pathways while considering the total cost of a net CO_2 reduction target (Al-Mohannadi et al., 2020). However, it is important to have a higher-level planning perspective to be able to assess and understand the solutions obtained from optimization. To address this gap, Lameh et al. (2021) developed a methodology for assessing and analyzing CO_2 reduction options through developing minimum marginal abatement cost (mini-MAC) curves which represent integrated systems consisting of various CO_2 reduction options. The approach uses high level parameters (costs and secondary emissions) to represent the different options based on their MAC and CO_2 reduction potential. The mini-MAC method assumes linearity of cost with CO_2 reduction for a given option, which may not apply when accounting for the temporal variations of energy supply and demand. The dynamics of the varying renewable energy sources and the fluctuating demand can play a major role in designing energy systems (Limpens et al., 2019). To our knowledge, there is no high-level cost analysis approach that can demonstrate the economic and environmental performances of CO_2 reduction strategies while considering the temporal variations in energy

Paper Received: 30 May 2021; Revised: 22 September 2021; Accepted: 10 October 2021
Please cite this article as: Lameh M., Al-Mohannadi D.M., Linke P., 2021, Cost Analysis for CO_2 Reduction Pathways, Chemical Engineering Transactions, 88, 583-588 DOI:10.3303/CET2188097

supply and demand and the effect of that on the design, sizing, and costs of the integrated system. Hence the contribution of this work is in proposing a high-level method for representing integrated systems while accounting for intermittencies and temporal variations of energy supply, demand, and storage. The proposed method is a two-step approach which identifies the proper sizes of the energy system components and the corresponding costs, considering the availability of resources and the demand. The mini-MAC profile of the integrated system is then developed based on the determined costs. The approach is represented through a case study based on the current situation of CO_2 emissions and energy resources availability in Qatar.

2. Methodology

This work considers the possibility of CO_2 reduction from a set of CO_2-emitting point sources by either implementing renewable energy (RE) options or by capturing and utilizing/storing the emissions. The aim is to understand the CO_2 reduction potential and the costs associated with the different achievable CO_2 reduction levels involving the implementation of the economically efficient pathways. This requires an integration between the environmental and the techno-economic performances of the considered options to determine the cost associated with the resulting CO_2 abatement. The proposed methodology is a two-step approach which starts by the identification of the minimum MAC (mini-MAC) of the different options while accounting for the dynamic variations in the supply of renewable energy, followed by the representation of the efficient options on a combined mini-MAC curve to analyze the performance of the integrated system. Figure 1 defines the scope followed for the considered technologies.



(a) (b)

Figure 1: Flow diagrams showing the scope of the considered (a) RES and (b) CCUS pathways

The first step of the approach is conducting an analysis for the individual options to determine their CO_2 reduction capacity and the MAC. For the renewable energy systems, the cost and the level of CO_2 reduction depend on the sizes of the RE generation and the RE storage units (Figure 1a). The energy security is ensured by assuming that the demand for power is always covered either by the RES (directly through the generated power or indirectly through discharging the stored energy) or by the backup fuel plant. This is done by performing the energy balance on each time step of the considered period, considering the RE generation and storage constraints which depend on the capacities of the RES components. In the case study shown in Section 3, hourly data throughout a typical year for the solar energy supply and for the demand for electricity is input into the method based on which the calculations are performed. The mini-MAC for the RES options corresponding to a certain level of CO_2 reduction is determined by varying the capacities of the RE generation and storage components, calculating their annualized costs, and calculating the power needed from the backup fuel-to-power plant and the corresponding CO_2 emissions. Eq(1) shows definition of the MAC for RES options. The mini-MAC profile is obtained by plotting the MAC against the CO_2 reduction level (Figure 2a).

$$MAC_{RES} = \frac{\text{total annualised cost of the energy system}}{flowrate\ of\ CO_2\ before\ implementing\ RES - flowrate\ of\ CO_2\ after\ implementing\ RES} \quad (1)$$

Considering the CCUS options, the mini-MAC is determined as described in Lameh et al. (2020), depending on the capture cost, the economics of the sink (CO_2 utilization or storage), and the secondary emissions. However, most technoeconomic studies of CO_2 utilization technologies do not consider the raw materials (other than CO_2) as part of the scope, but rather assume a price neglecting the environmental impact of attaining the feedstocks (Zimmermann et al., 2020). H_2 is a major feedstock when it comes to CO_2 utilization, as various processes depend on H_2 and CO_2 (like methanol, synthesized natural gas, Fischer Tropsch fuels, DME…). In this work, green H_2 is assumed to be generated through water electrolysis with the energy supplied from renewable sources (Figure 1b). This pathway is chosen since the aim is to reduce CO_2 through CCUS and green H_2 ensures that this goal is achieved. Hence, the cost of H_2 depends on the sizes of the electrolysis unit, the RE generation unit, and H_2 storage unit. Due to the temporal variations in the renewable energy sources, the sizing of the different components would depend on the time-based profile of renewable energy generation. The RE generation unit is sized so that H_2 supply to the utilization process, whether directly from the electrolyzer or from the storage, meets the H_2 requirements of the process throughout the operating period. The electrolyzer and the storage units are sized based on the maximum achieved operational loads. The price of H_2 can be determined based on the cost of the components, the price of H_2O required, and the profits from selling pure O_2. The economics of the sink process are characterized by the CO_2 breakeven cost which can be calculated as shown in Eq(2). After that, the MAC of the different CCUS options can be determined as presented by Eq(3).

$$CO_2 \text{ breakeven cost} = \frac{\text{profit from selling the product} - \text{cost of utilization process} - \text{cost of } H_2}{flowrate\ of\ utilized\ CO_2} \tag{2}$$

$$MAC_{CCUS} = \frac{cost\ of\ CO_2\ capture - \ CO_2 \text{ breakeven cost of utilization (or storage)}}{\text{CO}_2 \text{ fixation efficiency in the sink} - \text{secondary CO}_2 \text{ emissions from capture}} \tag{3}$$

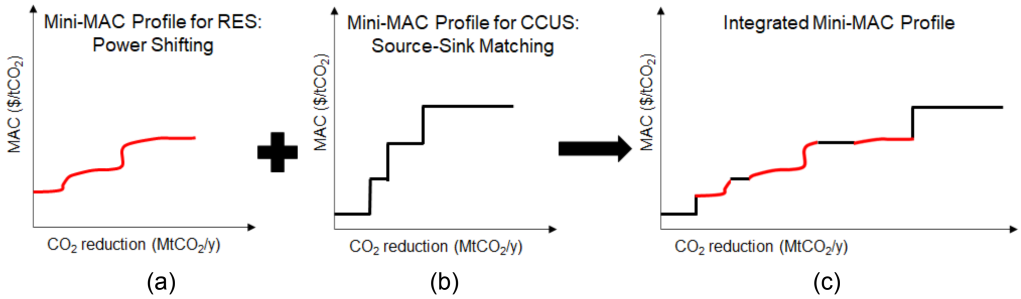


Figure 2: Mini-MAC of (a) the RES options, (b) the CCUS options, and (c) the integrated system

The MAC and CO_2 reduction potential of the different CCUS options corresponding to the various combinations between the sources and the sinks are determined as shown by Lameh et al. (2021) (Figure 2b). The second step of this approach is combining the mini-MAC profiles for the CCUS and RES options to analyze the cost and the CO_2 reduction potential of the integrated system (Figure 2c). Knowing the abatement costs of all the options, the different pathways are represented on a mini-MAC curve in increasing cost order to prioritize the cheapest options. CO_2 reduction via CCUS is constrained by the availability of the captured emissions and the capacity of the considered utilization and storage options. CO_2 reduction via RE options is constrained by the capacity of the RE technologies and the power demand. Analyzing the integrated mini-MAC curve allows the identification of the layout of the integrated system with reduced CO_2 emissions (Figure 3).

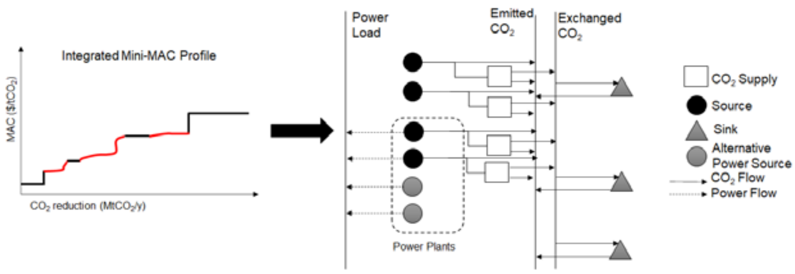


Figure 3: The integrated system with low CO_2 emissions as determined from the integrated mini-MAC curve

3. Case study

The described methodology is applied to a system consisting of CO_2 emitting sources which data (Table 1) is obtained based on the case of Qatar. The high purity sources include the processes in which CO_2 is captured and emitted in high concentrations, and the corresponding emissions flowrate is based on the operation of GTL and LNG plants (Alfadala and El-Halwagi, 2017). Qatar is a major natural gas (NG) producer, and NG combustion is the main source of energy for industrial heating and power production. The emissions flow rate for the NG combustion is based on the heat requirements of the different industrial plants operating in Qatar. The emissions flow rate from the NG power plant is based on the power demand covered by the existing power plants (Kahramaa, 2018). CO_2 capture costs and secondary emissions are based on Metz et al. (2005), Leeson et al. (2017), and von der Assen et al. (2016). The data for the considered sinks is obtained from different techno-economic studies for the utilization of CO_2 with H_2 to produce methanol (Pérez-Fortes et al., 2016), synthesized natural gas – SNG (Chauvy et al., 2021), and Fischer Tropsch fuels – FT fuels (Zang et al., 2021). The costs of the processes, the direct and indirect CO_2 emissions, and the CO_2 and H_2 requirements are obtained from the mentioned studies. Solar energy is considered as the RE option where power is generated through photovoltaic (PV) modules. The hourly solar power generation data (kW/kWp) is determined from the PVGIS model (PVGIS, 2016) assuming 14 % losses in the system. The costs of the PV-module, the electrolyzer, and the H_2 storage are determined based on IRENA (2020) and Nordin and Rahman (2019). The sizing of the PV system, the electrolyzer, and the H_2 storage for each of the considered sinks is performed as discussed in section 2, and the CO_2 breakeven costs are determined accordingly (Eq(2)). The costs of enhanced oil recovery (EOR) and CO_2 storage are based on Hepburn et al. (2019) and GCCSI (2011). The data used for the different sinks processes is shown in Table 2.

Table 1: Data collected for the CO_2 sources

Sources	Emissions Flowrate (tCO_2/y)	Capture Cost (\$/tCO_2-captured)	Secondary CO_2 (tCO_2/tCO_2-captured)
High Purity Sources	8.3	4.7	0.06
NG Combustion	54.1	34.6	0.24
NG Power Plant	25.4	34.6	0.24
Cement	2.21	60	0.24

Table 2: Data collected for CO_2 utilization and storage options

Sinks	H_2 Intake (tH_2/tProduct)	CO_2 Intake (tCO_2/tProduct)	CO_2 Breakeven Cost (\$/CO_2)	Capacity (tCO_2/y)	Fixation Efficiency
EOR	NA	NA	45	0.75	100 %
Methanol	0.2	1.46	-380	1.46	91 %
Methane	0.45	2.41	-852	10	98 %
FT Fuels	0.635	6.8	-394	6.82	43 %
Storage	NA	NA	-20	10	100 %

For designing the RES, solar energy is considered through PV modules and lithium-ion battery energy storage system (BESS). The hourly profile of the power load throughout a conventional year is determined based on Kahramaa (2018). The solar power generation is determined from the PVGIS model (PVGIS, 2016) based on the location of Qatar and assuming 14 % losses in the system. The capital cost of PV is 715 \$/kWp and the operation and maintenance (O&M) costs are assumed to be 10 \$/kWp/y (IRENA, 2020). The BESS has a capital cost of 400 \$/kWh, an O&M cost of 4 \$/kWh/y, and 2,000 full life cycles (Mongird et al., 2020). The first step of the methodology is applied for the collected data to obtain the CO_2 break even costs (Table 2) and the mini-MAC profiles for the different RES and CCUS pathways. Figure 4 shows the separate profiles of the mini-MAC obtained for the RES and CCUS options.

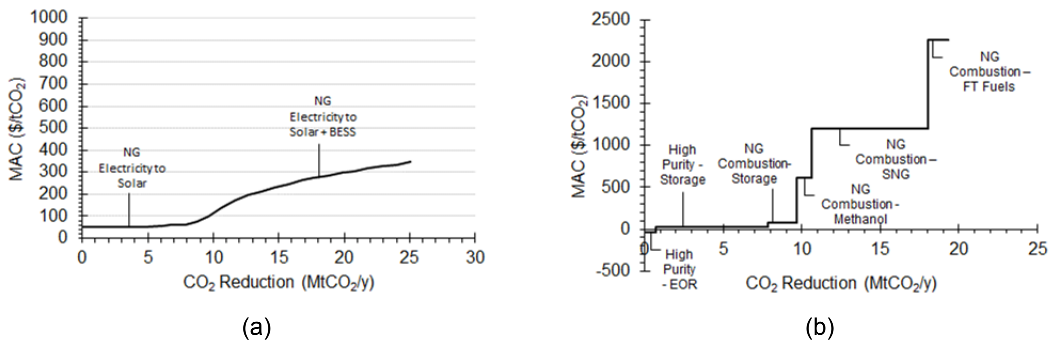
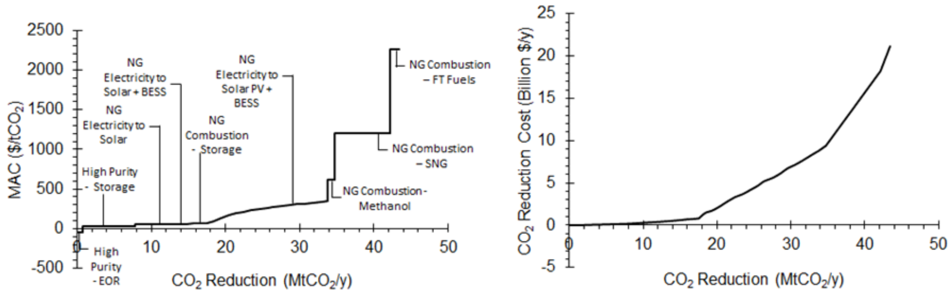


Figure 4: The minimum marginal abatement cost (mini-MAC) curves for (a) RES and (b) CCUS options

The results show a slight opportunity of profiting from CO_2 reduction through utilization of high purity emissions in EOR. The profitable CO_2 reduction is around 0.71 $MtCO_2$/y. Such profit can be used to fund the storage of CO_2 from high purity sources resulting in a cost-neutral CO_2 reduction of 1.85 $MtCO_2$/y. The implementation of PV is competitive compared to CO_2 capture and storage from NG combustion, having similar MAC and CO_2 reduction potential. However, the cost of RES rises when BESS is required to cover further electricity demand. Nonetheless, the RES option remains much cheaper than the expensive utilization options of CO_2 (methanol, SNG, and FT fuels).



(a) (b)

Figure 5: (a) Integrated mini-MAC profile and (b) the cost of CO_2 reduction

The mini-MAC profile of the integrated CO_2 reduction system is shown in Figure 5a. The integrated profile is obtained by combining the MAC and CO_2 reduction potential of both RES and CCUS options, ensuring that the cheapest options are prioritized. Analyzing the profile allows the determination of the cost of CO_2 reduction (Figure 5b) and the design of the system (the capturing sources, the implemented sinks, and the implemented power options) which achieves a set CO_2 reduction target (Figure 6). The results show that up to 19.5 % of the considered CO_2 emissions (17.5 $MtCO_2$/y) can be reduced through implementing solar power from PV (without the need for storage), and allocating CO_2 from high purity sources and natural gas combustion to EOR and storage. Such pathways result in an average CO_2 reduction cost of 45 $/tCO_2$. Further CO_2 reduction requires the implementation of more expensive options such as electricity storage and CO_2 utilization to produce chemicals and fuels. Solar energy has the potential of replacing natural gas power through combining PV with BESS. The required capacities of PV and BESS are 34 GWp and 132 GWh. The integrated system with CCUS (considering EOR and storage) can reduce up to 33.8 $MtCO_2$/y at an average cost of 261 $/tCO_2$. The implementation of all the considered options requires full replacement of natural gas power, capturing CO_2 from high purity sources and natural gas combustion, and operating all the sinks at their full capacities. This allows achieving a CO_2 reduction target of 48.3 % of the considered emissions at a high average cost reaching 488 $/tCO_2$. The high costs associated with the introduction of BESS and CO_2 utilization (methanol, SNG, FT-fuels) are attributed to the high costs of energy storage and H_2 production and storage. Hence, major breakthroughs are required to reduce the costs of these technologies to make the economic reduction of CO_2 possible at reasonable prices.

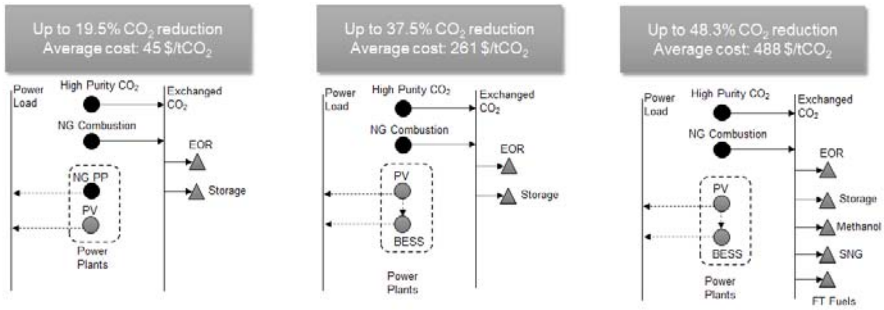


Figure 6: Different designs for the CO_2 reduction system corresponding to different levels of CO_2 reduction

4. Conclusion

This work proposed a novel high-level cost analysis method for CO_2 reduction pathways that is able to account for the effect of the intermittency of the renewable energy sources and the temporal variations in the demand for power on the economic and environmental performances of RES and CCUS options. The method was applied to a case study to demonstrate the significant insights that can be determined. It was shown that for the case of Qatar, solar power and CO_2 capture, utilization in EOR, and sequestration can play a key role in an economic CO_2 reduction. Such pathways can reduce up to 17.5 $MtCO_2$/y with an average cost of 45 $/tCO_2$. Further CO_2 reduction can be achieved by introducing battery storage (up to 33.8 $MtCO_2$/y) and CO_2 utilization for chemicals production (up to 43.5 $MtCO_2$/y); however, the average cost of CO_2 reduction would rise significantly to 261 $/tCO_2$ and to 488 $/tCO_2$. Future work will further analyse the sensitivity of the CO_2 reduction price relative to the expected reductions in costs associated with the improvement of the existing technologies.

References

Al-Mohannadi D. M., Kwak G., Linke P., 2020, Identification of optimal transitions towards climate footprint reduction targets using a linear multi-period carbon integration approach, Computers and Chemical Engineering, 140, 106907.

Alfadala H. E., El-Halwagi M. M., 2017, Qatar's chemical industry: Monetizing natural gas, Chemical Engineering Progress, 113(2), 38-41.

Chauvy R., Verdonck D., Dubois L., Thomas D., De Weireld G., 2021, Techno-economic feasibility and sustainability of an integrated carbon capture and conversion process to synthetic natural gas, Journal of CO2 Utilization, 47, 101488.

GCCSI, 2011, The costs of CO2 storage: post-demonstration CCS in the EU, Global CCS Institute, Brussels, Belgium.

Hepburn C., Adlen E., Beddington J., Carter E. A., Fuss S., Mac Dowell N., Minx J. C., Smith P., Williams C. K., 2019, The technological and economic prospects for CO2 utilization and removal, Nature, 575(7781), 87-97.

IEA, 2021, Net Zero by 2050, International Energy Agency, Paris. <www.iea.org/reports/net-zero-by-2050> accessed 31.08.2021.

IRENA, 2020, Renewable Power Generation Costs in 2019, International Renewable Energy Agency, Abu Dhabi, United Arab Emirates.

Kahramaa, 2018, Kahramaa Annual Statistics Report 2018, Qatar General Electricity and Water Corporation, Doha, Qatar

Lameh M., Al-Mohannadi D. M., Linke P., 2020, Developing Minimum Cost Targets for Carbon Reduction in Different Geographical Regions, Chemical Engineering Transactions, 81, 97-102.

Lameh M., Al-Mohannadi D. M., Linke P., 2021, Minimum marginal abatement cost curves (Mini-MAC) for CO2 emissions reduction planning, Clean Technologies and Environmental Policy, 1-17. DOI:10.1007/s10098-021-02095-y

Leeson D., Mac Dowell N., Shah N., Petit C., Fennell P., 2017, A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources, International Journal of Greenhouse Gas Control, 61, 71-84.

Limpens G., Moret S., Jeanmart H., Maréchal F., 2019, EnergyScope TD: A novel open-source model for regional energy systems, Applied Energy, 255, 113729.

Metz B., Davidson O., De Coninck H., 2005, Carbon dioxide capture and storage: special report of the intergovernmental panel on climate change, Cambridge University Press, New York, United States of America.

Mongird K., Viswanathan V., Alam J., Vartanian C., Sprenkle V., Baxter R., 2020, 2020 Grid Energy Storage Technology Cost and Performance Assessment. Energy, U.S. Department of Energy, DOE/PA-0204, <www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf > accessed 31.08.2021.

Nordin N. D., Rahman H. A., 2019, Comparison of optimum design, sizing, and economic analysis of standalone photovoltaic/battery without and with hydrogen production systems, Renewable Energy, 141, 107-123.

Pérez-Fortes M., Schöneberger J. C., Boulamanti A., Tzimas E., 2016, Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment, Applied Energy, 161, 718-732.

PVGIS, 2016, Photovoltaic geographical information system. European Commission. <re.jrc.ec.europa.eu/pvg_tools/en/#PVP> accessed 31.08.2021.

Thonemann N., Pizzol M., 2019, Consequential life cycle assessment of carbon capture and utilization technologies within the chemical industry, Energy and Environmental Science, 12(7), 2253-2263.

von der Assen N., Müller L. J., Steingrube A., Voll P., Bardow A., 2016, Selecting CO2 Sources for CO2 Utilization by Environmental-Merit-Order Curves, Environmental Science and Technology, 50(3), 1093-1101.

Zang G., Sun P., Elgowainy A. A., Bafana A., Wang M., 2021, Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process, Journal of CO2 Utilization, 46, 101459.

Zimmermann A., Müller L., Wang Y., Langhorst T., Wunderlich J., Marxen A., Armstrong K., Buchner G., Kätelhön A., Bachmann M., 2020, Techno-Economic Assessment and Life Cycle Assessment Guidelines for CO2 Utilization, University of Michigan, Ann Arbor, United States of America (Version 1.1).