On the Economics of Solar Chemical Processes – Case Study for Solar-Co-Production of Methanol and Power

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Abstract

In several studies, the efficiency of solarized industrial processes was assessed and showed promising results. However, the economic competitiveness of such processes is a mainly unanswered question. In this work, the economic performance of a solar aided methanol production process is determined. The assessment yields promising results for the considered co-production process. The presented results also show that for a penetration of renewable energies beyond electricity production, the common support model of fixed feed-in-tariffs is not suitable. A reasonable cost for CO_2 emissions or reward for their reduction will allow finding the most economic application for renewable energies independent of the end product of the process. When reasonable rewards of 75 $\$/t_{CO2}$ for the reduction of CO_2 emissions compared to fossil reference processes are considered, the process can produce methanol and electricity at competitive prices.

Keywords: Solar thermochemistry, CSP, solar fuels, reforming, economics

1. Introduction

The necessity to reduce greenhouse gas emissions by substituting fossil energy carriers by renewable energy sources such as solar- and wind energy is widely accepted and ongoing today. Regarding the production of electricity, this process has already well advanced in several countries. For instance, in Germany more than 30 % of the electricity was produced from renewable energies in 2015 [1]. However, as also increasingly discussed, the implementation of renewable energies has to advance towards industrial processes to achieve a complete energy transition. von Storch et al. [2] as well as Bai et al. [3] proposed processes for production of methanol with the aid of solar energy that also include further energy streams into and out of the process. In both publications, solar energy is concentrated (i.e. concentrated solar power (CSP)) to provide high temperature heat. Furthermore, both give promising results for the processes regarding the efficiency of solar energy utilization. However, for new renewable energy applications to be commercialized, favorable economics are necessary. Bai et al. [3] give an estimation on economic performance and show methanol prices between 440 and 516 $/t, but they are not put into context with market prices and common costs for renewable energy utilization. In von Storch et al. [2], economic aspects of the proposed process are not assessed at all. On the one hand, it is necessary to determine product costs for such processes to assess their potential to become commercially viable. On the other hand it is also necessary to carry out an economic assessment in order to carry out process optimization. For instance, as stated by von Storch et al. [2], the possibility of implementing thermal energy storage to increase operating hours of the investigated process is a central advantage of the considered technology. However, implementation of thermal energy storage can only enhance the economic performance, and not the efficiency. Hence, the suitable storage size can only be determined through economic optimization of a process. The same applies for the solar multiple, which represents the energy provided by the solar part at nominal operation in relation to the nominal energy input into the reforming process. The larger the solar multiple, the higher the capacity factor for the reforming process, but the larger and more expensive the solar receiver and heliostat field. Therefore, the optimal solar multiple can only be found through economic considerations.

In order to close the gap regarding information on the performance of these processes, the process presented by von Storch et al. [2], which is based on solar aided reforming of natural gas for methanol production (SOLME process), is assessed regarding its economic performance in this work.

2. The SOLME Process

The SOLME process presented by von Storch et al. [2] is a process that produces methanol and electric power form

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concentrated solar radiation and natural gas. A simplified flowchart of the process is presented in Figure 1. To provide the concentrated solar irradiation, a solar power tower is used: A heliostat field concentrates solar irradiation onto a central receiver where the irradiation is absorbed and converted into heat. As central receiver, an open volumetric receiver, as thermal storage a ceramic brick storage, both similar to the system installed at the solar tower Jülich (cf. Alexopoulos and Hoffschmidt [4]) are considered. Air is used as heat transfer fluid and transports the heat from the receiver or thermal storage to the reforming reactor. In the reforming reactor natural gas is converted into syngas via the reforming reaction. The syngas is cooled, compressed and given into a methanol synthesis reactor, where it is converted into methanol. Due to a large recycle stream in the methanol synthesis, it is necessary to purge an off-gas. This off-gas consists of inert species as well as unreacted methane, hydrogen and carbon monoxide. Hence it has a significant heating value. It can be combusted to provide heat to the reforming reactor or co-combusted in a power plant, for instance a combined cycle gas turbine power plant (CCGT). The off heat that is available from syngas cooling and as heat of reaction from methanol synthesis cannot be completely integrated into the process. It is considered, that the heat is used in a water-steam cycle to generate additional electricity. A more detailed description of the SOLME process can be found in refs [2, 5].

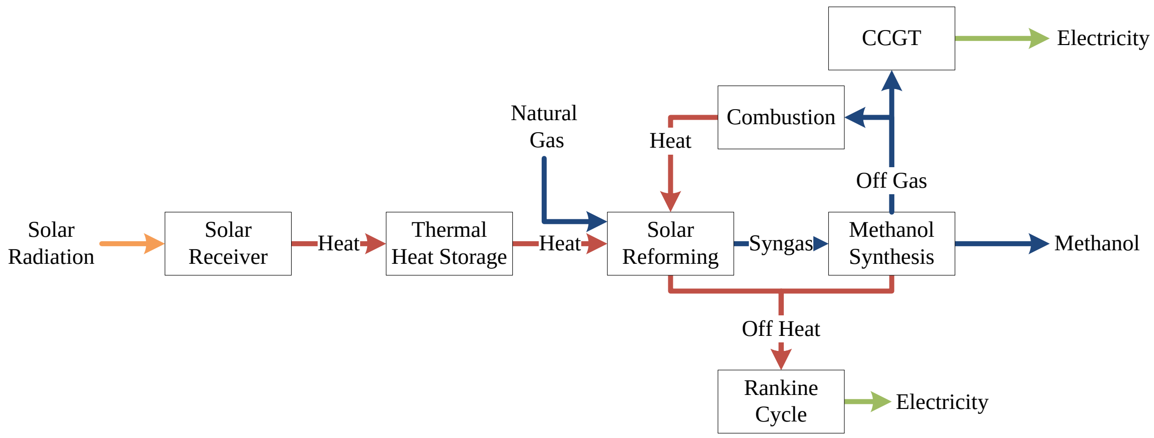

Figure 1 – Schematic of the SOLME process

As can be seen in Figure 1, the process consumes solar energy, natural gas and water to produce electricity and methanol. The production of two products from a renewable and a fossil energy resource complicates the economic assessment. Usually the utilization of renewable energies makes the product more expensive. In the case of facilities for the production of electricity, this is taken care of by increased feed-in-tariffs; which act as subsidy. For methanol production facilities, this procedure is not known.

Regarding the energetic performance of the process, von Storch et al. [2] report that the SOLME process can produce a given amount of electricity and methanol from the same amount of solar energy but approx. 5 % less natural gas than a system of conventional methanol synthesis and solar power plant. This indicates that the hybrid process for methanol and power production is more efficient regarding natural gas consumption than a separate production of solar power and conventional methanol would be. They state that the SOLME plant, that is scaled by the solar receiver with a capacity of 50 MW produces 127.5 GWh of Methanol and 21.41 GWh of electricity per year from 176.1 GWh of solar energy (onto heliostat field) and 148.4 GWh natural gas. The same size SOLME plant is assessed in this work. However due to the parameter variations, which are mentioned in the following chapter, the amounts of methanol and electricity produced will vary.

3. Methodology and procedure

Several options exist for the economic assessment of a process such as the SOLME that produces two products. Firstly, realistic market price for the products can be retrieved from a suitable source and the achievable profit can be determined based on capital cost and operational cost. However, as this would lead to negative profits for most processes that use renewable energy resources, for processes using renewable energy resources the concept of *levelised cost of electricity* (LCOE) is commonly used [6]. In this concept, the capital cost and operational cost (C_{OPEX}) of the process are determined. The capital cost is usually taken into account as the annuity of the initial investment ($C_{Annuity}$), considering a certain weighted average cost for capital (WACC). By division of the total cost with the amount of produced electricity, the LCOE is determined, as shown in equation (1). The resulting value indicates the minimum electricity price, to achieve the required interest rate/profit. This concept can also be applied to other products than electricity, for instance to methanol. However, it cannot be applied in the same way to processes, which produces two products such as the SOLME process. Therefore, for this process, a realistic price for methanol (c_{Methanol}) is considered and the revenues subtracted from the annual costs in determining the LCOE. The resulting equation is shown in (2), where $m_{\mathrm{Methanol,SOLME}}$ is the annual amount of methanol produced in the process. The LCOE determined through this procedure can subsequently be compared with other processes. Then the LCOE is also the objective criterion to be minimized.

$$LCOE = \frac{C_{Annuity} + C_{OPEX}}{E_{El}} \tag{1}$$

$$LCOE_{\mathrm{SOLME}} = \frac{C_{\mathrm{Annuity,SOLME}} + C_{\mathrm{OPEX,SOLME}} - m_{\mathrm{Methanol,SOLME}} \cdot c_{\mathrm{Methanol}}}{E_{\mathrm{El,SOLME}}} \tag{2}$$

It is aimed to minimize the LCOE by variation of two central parameters: Solar multiple and thermal storage size. The solar multiple is defined as the nominal thermal capacity of a receiver in relation to the nominal thermal input of the reforming process. The heliostat field is size is fixed to provide sufficient concentrated solar irradiation to the receiver for nominal operation at noon of the 21st of March, which is a flux of 50 MW. The procedure is presented in detail by von Storch et al. [2]. The resulting heliostat field has a size 62,854 m² at the location in In Amenas in Algeria. The solar multiple is varied by scaling the non-solar part of the SOLME process. This means that the solar energy collected by the heliostat field and transformed into thermal energy in the solar receiver is fixed, the time period over which the process consumes and the amount that has to be dumped because the storage is full are varied. Energy consumption for operation of the heliostat field are taken into account as parasitic losses based on data published in the ECOSTAR report [7], where 6.5 W_{el} per square meter of heliostat field are stated. This results in a total consumption of 408.6 kW during solar operation. Based on heliostat field layout, the solar operating time is 4383 hours per year. Other major parasitic losses, such as blower for the air system are taken into account in the process model directly.

Despite a rapid reduction in costs for renewable energy technologies, processes that use renewable energy resources usually still have a higher cost of product than processes that use fossil fuels. This can be well observed at recent solar power projects, such as the recently inaugurated solar power plant *crescent dunes*. Besides subsidized loans, this kind of solar power plant is mainly supported through an increased feed-in-tariff, in this case 135 $/MWh [8] (the market price of electricity in that region is approx. 80 $/MWh [9]). The total subsidy for the project through increased feed-in-tariff can be estimated by multiplication of the difference in electricity price (in this case approximately 55 $/MWh) with the total amount of electricity produced. In the case of the SOLME plant, compared to a conventional solar power plant of identical scale, less electricity is produced because a fraction of the solar energy input is used in the methanol production. However, as the methanol is sold at a conventional market price (cf. paragraph above), the additional cost due to the solar field, receiver, etc. is spread over a lower amount of electricity. Hence, the resulting LCOE will be higher than for a conventional solar power plant even if the economic performance of the SOLME plant may be better. Therefore, comparison of the LCOE of the SOLME plant with published LOCEs of real solar power plants will lead deceptive conclusions.

To compare the economic performance of the SOLME process and conventional solar plants realistically, the total necessary subsidy to achieve marketable product prices should be determined. This can be done in several ways, for instance by considering a fixed annual sum or by considering a *reward* for the reduction of CO_2-emissions compared to the state of the art. In this work, both is done. Considering rewards for the reduction of CO_2-emissions is especially interesting, as it could be an effective measure to help achieving the superordinate goal in renewable energies utilization: The reduction of greenhouse gas emissions. Through this procedure, the more economic route for reduction of greenhouse gas emissions through solar energy utilization can be determined; in this case between a conventional solar power plant and the SOLME plant. Therefore in a parameter variation, the results for LCOE are determined in dependence of reward for reduction of carbon dioxide emission. The reward is varied between 0 and 200 $\$/t_{CO2.}$ This reward can be considered as a potential income from excess CO_2 certificates as they exist in the EU. Currently the prices of the certificates are below 10 €/t (cf. https://www.eex.com/de/). However, they are expected to rise in the future and achieve values up to 76 €/t (100 $/t) according to Schlesinger et al. [10].

In order to obtain a comparable and realistic price for methanol, the price is determined based on own simulations rather than obtaining data from literature or real market prices. This ensures that comparable assumptions and boundary conditions are used for the SOLME process and the reference methanol price. The determination of reference methanol price is based on the process used as reference methanol process for energetic performance assessment by von Storch et al. [2]. The resulting value is 180$/t$_{Methanol}$. However, the value is varied to determine if it will affect the optimum values for storage size and solar multiple. In the case of the reference solar power plant, the receiver and storage size as well as solar multiple are set to the same values as in the SOLME process to ensure comparability of the results. This is done to obtain a comparable plant regarding the duration of which it can provide electricity to the grid throughout the year.

Determining the capital cost of SOLME process

The capital cost of the processes can roughly be categorized as conventional process units and CSP components. The cost of conventional process units is determined according to data by Ulrich and Vasudevan [11] and the prices converted from 2004 to prices of 2014 with the chemical engineering cost index (CEPCI) [12, 13]. The calculation is done in US-$. If prices are retrieved in other currency, it is converted to US-$ with the average exchange rate applicable for the year of publication from [14]. In accordance with Ulrich and Vasudevan [11], the bare module component costs (C_{BM}) are multiplied by a factor of 1,534 to yield the grass roots cost (C_{GR}), which includes fees and contingencies as well as auxiliary facilities, i.e. represents the total investment.

The prices for CSP-related components are retrieved from the ECOSTAR Report [7] and Vogel and Kalb [15]. The values used for the components are given in Table 1. Some of the data used to determine the prices of CSP components is several years old already. It is well known that significant cost reductions were achieved in the meantime. However, no reliable, detailed data is publicly available. Therefore, based on the predictions by Trieb [16], a reduction in CSP-Component cost by 30 % are assumed to take into account current developments.

Table 1 – Cost data for CSP components

Component	Source	Value and basis in source	In 2014-$	30 % reduced value
Tower	ECOSTAR Report [7]	2 mio. €$_{2003}$	3.55 Mio. $	2.73 mio. $
Heliostat Field	Vogel and Kalb [15]	100 $$_{2002}$/m²	146.64 $/m²	102.65 $/m²
			9.22 Mio. $ (total)	6.45 mio. $
Receiver	ECOSTAR Report [7]	115 €$_{2003}$/kW$_{th}$	204 $/kW$_{th}$	142.8 $/kW$_{th}$
Storage	ECOSTAR Report [7]	60 €$_{2003}$/kWh$_{th}$	106 $/kWh$_{th}$	74.2 $/kWh$_{th}$

The price of the Rankine cycle (RC) of the reference solar power plant is based on information from the ECOSTAR Report [7] according to equation (1) in dependence of the of its nominal electric output, assuming a value of 0.6 as scaling factor as recommended by Ulrich and Vasudevan [11].

$$C_{\mathrm{BM,PB}} = 1{,}064{,}400\,\frac{\$}{\mathrm{kW}} \cdot \left(\frac{P_{\mathrm{RC,el,nom}}}{10\ \mathrm{MW}}\right)^{0.6} \qquad \text{(eq. 1)}$$

For the combustion of the off-gas in a CCGT, it is assumed that it is co-combusted in an industrial scale CCGT rather than building a small scale CCGT for this purpose only. Therefore, the specific cost for a 200 MW CCGT plant are determined based on information from Ulrich and Vasudevan [11] and the fraction of capacity that can be attributed to the SOLME plant is considered in the investment cost. The specific cost (grass roots) is 3250 $/kW$_{el}$.

Further relevant parameters for calculation of annuity and operating costs of the plant are given in Table 2. The WACC and expected lifetime are based on values proposed by Dieckmann et al. [17] for the near term future. The operation and maintenance cost (O&M) of CSP related components are set to 2% of the investment per year in accordance with Hernández-Moro and Martínez-Duart [18]. The O&M cost factor is set to 0.5% for all other components. The cost for demineralized water is determined with information provided by Ulrich and Vasudevan [11]. As cost for natural gas, based on the average values published for Henry Hub spot price between 2010 and 2016 [19], a value 0.012$/kWh (3.5 $/MBtu) is assumed.

Table 2 – Annuity input data for SOLME plant

Parameter		Value
WACC		6.5%
Payback time		25 years
O&M		
	CSP – related components	2 % of investment/year
	Other components	0.5 % of investment/year
	Cost for demineralized water	0.35 Mio. $/year
Natural gas price		0.012 $/kWh

Determining CO_2-emissions reduction

The CO_2-emissions reduction is estimated by the difference in natural gas consumption compared to a benchmark value. In the case of methanol production, benchmark is based on a conventional methanol production plant based on the information by von Storch et al. [2]. In the case of electricity production, the benchmark is based on a CCGT plant. Indirect CO_2-emissions are not taken into account in this case, as it is assumed that they are similar for all processes.

Based on the composition of the natural gas and the molar weight of CO_2, 42.6 $t_{CO2}/Mmol_{Natural\ Gas}$ are considered. This leads to specific emissions of 1.865 $t_{CO2}/t_{Methanol}$ as benchmark value. For electricity production, a CCGT with 60 % efficiency is assumed for the benchmark. Based on the same natural gas composition, this leads to specific emissions of 416 t_{CO2}/GWh_{el}. The reference solar power plant does not consume natural gas. Therefore, no CO_2-emissions are considered.

4. **Results & Discussion**

LCOE of SOLME process

At first, it was assessed, if the assumed methanol price has an influence on the optimum values for solar multiple and storage size. The results for LCOE of the SOLME process for different methanol prices are shown in Figure 2 in dependence of solar multiple and Figure 3 in dependence of storage size. In both figures, it can be seen that the assumed methanol price has a relevant influence on the LCOE, which was to be expected because the methanol revenues are higher when methanol prices are higher. Thus the remaining costs on which the LCOE is based are lower. Furthermore, it can be seen, that an optimum evolves for both solar multiple (approx. 3.4) and storage size (approx. 150), which is not dependent on methanol price in the considered range.

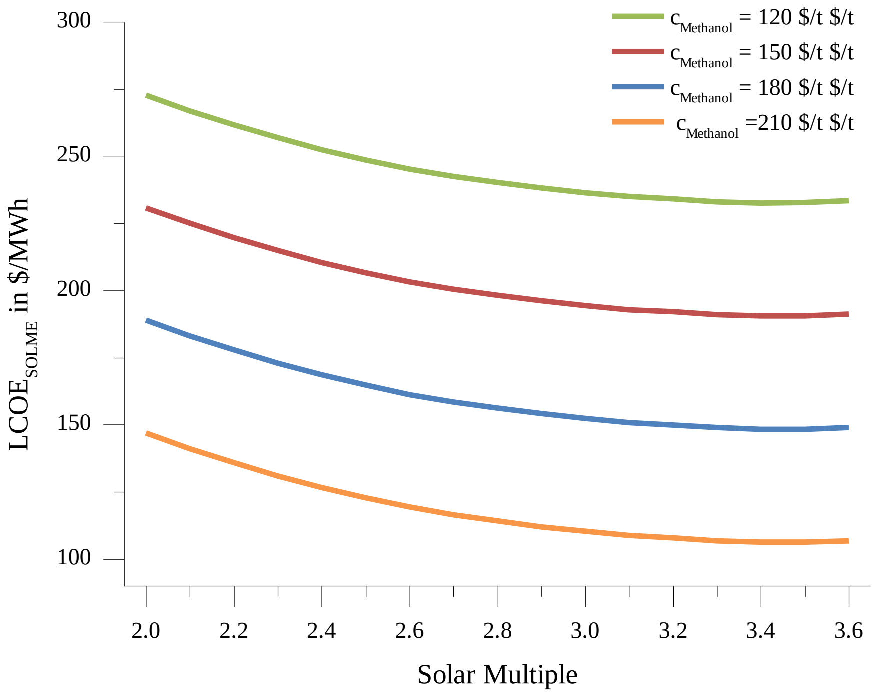

Figure 2 – LCOE for SOLME in dependence of Solar Multiple for different assumed methanol prices, assuming a storage size of 150 MWh

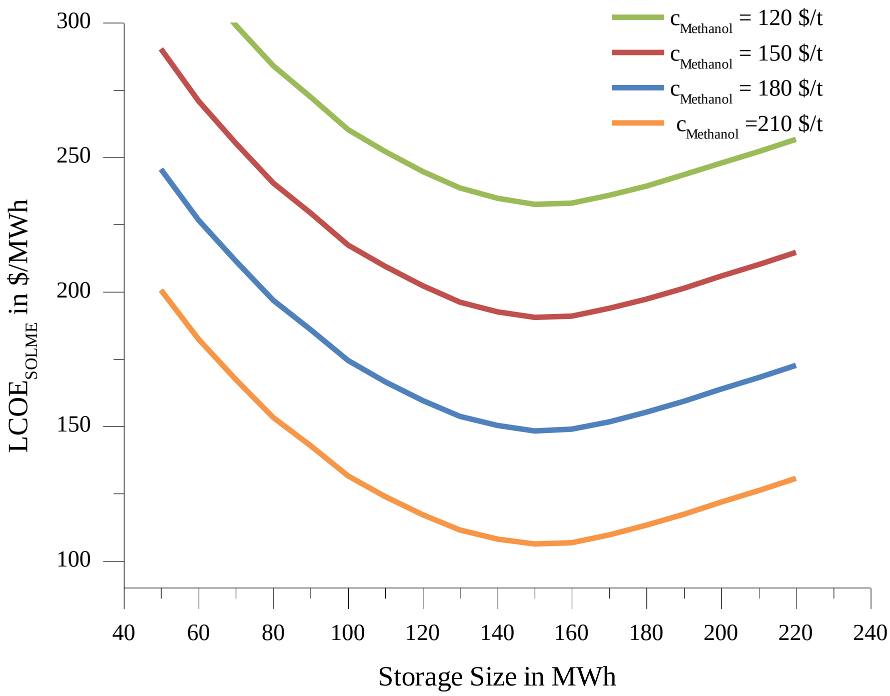

Figure 3 – LCOE for SOLME in dependence of thermal storage size for different assumed methanol prices, assuming a SM of 3.4

The results shown in Figure 2 and Figure 3 show that the optimum for the two considered optimization parameters can be found independently of the assumed methanol price. Hence it is justified to set the methanol price to a realistic value, which is 180 \$/t in this work.

In Figure 4, the results of the optimization of the LCOE by variation of solar multiple and storage size is shown. It can be seen that the lowest value for LCOE is achieved at a solar multiple of 3.4 and storage size of 150 MWh. The resulting value of LCOE is 148.3 \$/MWh. For the same storage size and solar multiple, the LCOE of the reference solar power plant is 124.4 \$/MWh.

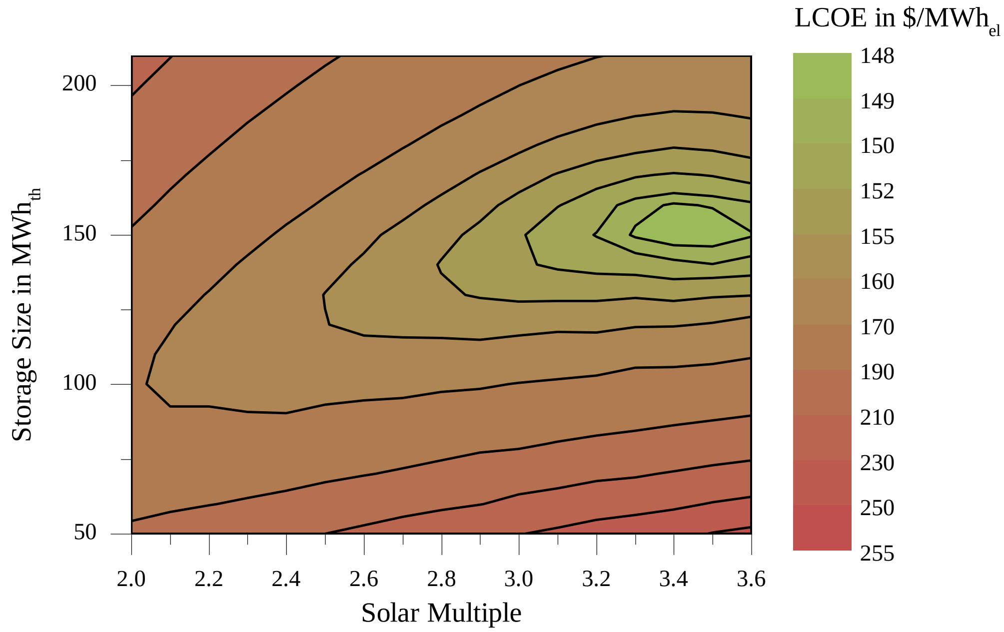

Figure 4 – Optimization of LCOE by variation of storage size and solar multiple

In the optimum configuration, the process achieves 7395 operating hours per year, which corresponds to a capacity factor of 86 %. This means that nearly continuous operation is possible, except for periods of continuously low solar irradiance during winter. Some further key results on the operation of the process at this configuration are given in Table 3. It can be seen that the nominal thermal input into the process is 10.74 MW. Consequently, with a 150 MWh thermal storage, a storage-only operation of 14 hours is possible. The results on process costs are summarized in Table 4.

Table 3 – Key parameters on the operation of SOLME with solar multiple of 3.4 and 150 MWh storage size

Parameter	Result
Nominal thermal input	10.74 MW
Dumped energy	3.61 %
Produced methanol	22,361 t/year
Produced electricity (net)	15.9 GWh/year

Table 4 – Key results on economic aspects of SOLME process for solar multiple of 3.4 and 150 MWh storage size

Parameter			Result
Total investment cost (grass roots price)			45.7 Mio. $
	Heliostat Field		6.5 Mio. $
	Solar Receiver		5.2 Mio. $
	Thermal Energy Storage		11.1 Mio $
	Non-Solar part		20.5 Mio. $
		Power block (1.40 MW)	5.93 Mio. $
		CCGT (2.27 MW)	4.63 Mio. $
		Air heated reforming reactor	2.36 Mio. $
Annual costs			6.39 Mio $
Annuity of investment			3.75 Mio. $
Operation & Maintenance (annually)			0.6 Mio. $
Natural gas consumption(annually)			1.68 Mio. $
Cost for demineralized water			0.35 Mio. $
Revenue methanol			4.03 Mio. $
LCOE			148.3 $/MWh

The reference solar power plant has an annual net production of electricity of 31.0 GWh with the same heliostat field as the SOLME plant at total investment costs of 37.9 Mio. $. The resulting annuity is 3.1 Mio. $, the operation and maintenance costs are 0.76 Mio. $, resulting in an LCOE of 124.4 $/MWh.

The necessary subsidy for each of the plants can be determined by multiplying the produced electricity with the difference between the LCOE and the market price. As proposed above, 80 $/MWh can be assumed as market price. For the SOLME plant, this yields a required annual funding of 1.086 Mio. $. For the reference solar power plant the required annual funding is 1.379 Mio. $. Hence, the SOLME process can be commercially viable with a lower funding than the conventional solar power plant.

Influence of reward for CO_2 emissions reduction on LCOE

The key results that are relevant to determine the influence of a reward for the reduction in CO_2-emissions are summarized in Table 5. The CO_2-emissions of the SOLME plant are compared with the previously defined benchmark values. No CO_2-emissions are considered for reference solar power plant. Therefore, it achieves a reduction in CO_2-emissions compared to the benchmark by 100 %. As can be seen in Table 5, the SOLME plant achieves a yearly reduction in CO_2-emissions by 13,197 t, the reference solar power plant by 12,909 t

Table 5 – Data on CO_2 Emissions of SOLME process, reference solar power tower and reference methanol plant and CCGT

Parameter		Result
Natural gas consumption (SOLME)		824 Mmol
CO_2-emissions		
	SOLME	35,132 t
	Benchmark Methanol (22.361 $t_{Methanol}$)	41,703 t
	Benchmark electricity SOLME (15.9 GWh_{el})	6,614 t
	Benchmark electricity SPT (31.0 GWh_{el})	12,909 t
Reduction of CO_2 Emissions by SOLME plant		13,197 t
Reduction by reference solar power plant (31.0 GWh)		12,909 t

The influence of a reward for the reduction of CO_2 emissions on the LCOE of the SOLME process as well as the reference solar power plant is shown in Figure 5. It can be seen that the LCOE is reduced with increasing reward. It can also be seen that the reduction is faster for the LCOE of the SOLME plant than for the reference solar power plant. This is caused by the higher reduction in CO_2-emissions of the SOLME process as indicated in Table 5. Without, or with low rewards, the LCOE of the SOLME plant is higher than the LCOE of the reference solar power plant. However, for a reward of 50 $\$/t_{CO2}$ or higher, the LCOE of the SOLME is lower than for the reference solar power plant. The SOLME plant achieves a competitive LCOE of 80 \$/MWh at a reward of 80 $\$/t_{CO2}$, while the conventional solar power plant only achieves this value at 110 $\$/t_{CO2}$. This shows that even without further CSP-component cost reduction, the SOLME process has the capacity to achieve competitiveness, if suitable funding mechanism, such as reasonably priced CO_2-emissions certificates exist.

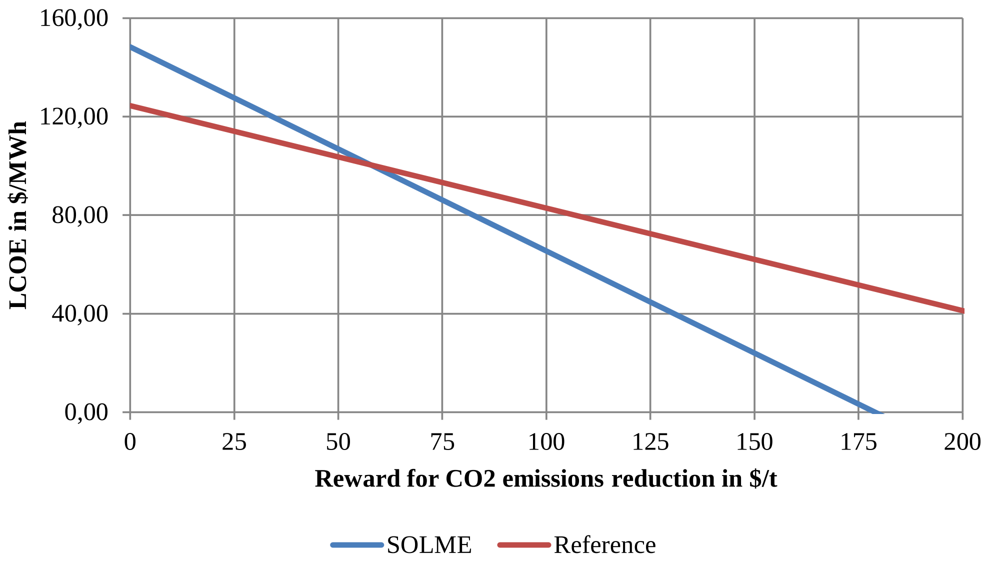

Figure 5 – Influence of reward for reduction of CO_2-emissions on LCOE

5. Summary and Conclusions

The economic performance of a process for hybrid solar-fossil co-production of methanol and electric power (SOLME process) is assessed. A reasonable price for methanol is fixed and the resulting levelized cost of electricity (LCOE) is determined. The solar multiple and thermal storage size are varied to optimize the economic performance and find the minimum LCOE. A value of 148.3 \$/MWh is achieved for a solar multiple of 3.4 and a thermal storage size of 150 MWh, which allows up to 14 hours of off-sun / storage-only operation.

The resulting LCOE is higher than for a comparable solar power plant that produces only electricity, which would achieve 124.4 \$/MWh. This is the case, because the additional cost of the CSP-components is spread over a lower amount of electricity, when the methanol is sold at market price. By determining the required subsidy to achieve competitive operation independent of product, it is shown that the SOLME process is closer to commercial viability. For electricity from renewable resources, power purchase agreements are commonly concluded with electricity prices higher than the market price. This is caused by the requirement of many utility services to reduce their overall CO_2 emissions. This practice does not exist for commodities such as methanol. A suitable mechanism to support the utilization of renewable energies in commodities production could be reasonably priced certificates for CO_2-emissions. When considering a possible reward for the reduction of CO_2-emissions, favorable results for the SOLME process are obtained. Because it causes a higher reduction in CO_2-emissions than a conventional solar power plant, it achieves a competitive LCOE of $80\$/MWh_{el}$ at a reward of 80 $\$/t_{CO2}$. The conventional solar power plant would require a reward of 110 $\$/t_{CO2}$ to achieve the same LCOE. This also shows that the SOLME process requires lower subsidy to become commercially competitive than a conventional solar power plant.

In conclusion it can be stated that the SOLME process achieves a very promising economic performance, even at current CSP component prices. However, currently no effective funding mechanisms exist to support the production of less carbon intensive commodities.

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