Sunlight Production
of Chemical Fuels

SPOTLIGHT

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D6.4 Report about the techno-economic assessment of plasmon conversion processes

WP6 Techno-economic and environmental assessment

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EXECUTIVE SUMMARY

In this deliverable we report about the techno-economic analysis of the SPOTLIGHT processes that has been developed and evaluated in WP5. We show a preliminary system design for a scaled-up facility of 100 kton to produce either CH_4 in the Sabatier process or CO in the reverse water-gas shift process. The system can be operated in three different configurations, which relate to the key research questions of the project. In the first configuration, the process is driven by a LED system. In the second configuration, the LED light is assisted by a solar concentrator system that only operates when the sun shines. The third configuration only operates based on the solar concentrator system. We first assess the costs of these systems and configurations based on the experimental data. Next, we explain potential improvements for the processes based on insights from the experimental campaign. This provides for each of the processes an advanced case, which we analyze in a similar fashion.

According to the analysis, the SPOTLIGHT processes are currently highly capital intensive. Especially the LED-based configurations suffer from high LED costs and in combination with a high and expensive electricity consumption. These routes are unlikely to compete with the solely sunlight-driven processes analyzed in configuration 3. Further developments may substantially improve the performance of the process, both for Sabatier and for RWGS. Effects are largest for RWGS because of the relatively low conversion and throughput that was obtained during the experimental campaign. For Sabatier, the advanced case of the sunlight-driven configuration 3 shows the most promise and can reach CH_4 production costs of 123 € GJ^{-1}. Even when capital costs can be further reduced, the process relies significantly on the H_2 feedstock costs as these contribute around 40% to the total. Lower green hydrogen prices are therefore also essential to reach competitiveness with carbon-taxed natural gas prices. Similar to Sabatier, also for RWGS the advanced case configuration 3 shows the most promise and can reach CO production costs of 154 € GJ^{-1}. This route can reach break-even costs with the fossil benchmark price in combination with a carbon tax of around 500 € ton^{-1} of CO_2. As H_2 and CO_2 as feedstocks together contribute for almost 30%, a change in their feedstock price may have a substantial effect on the production costs.

Only when the performance can be even further improved and LED lights and electricity can reduce substantially in costs, the LED-based configurations can become cost competitive with the sunlight-driven case. Under these circumstances, a carbon tax of around 300 € ton^{-1} of CO_2 would be sufficient to reach break-even with the fossil price. We recommend to further explore the influence of other effects on the process, such as flexible operation and storage, and investigate potential integration with a follow-up syngas conversion route. Also, the application of similar plasmon conversion processes, either with or without LED system, in different types of chemical reactions can be of research interest.

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REPORT ABOUT THE TECHNO-ECONOMIC ASSESSMENT OF PLASMON CONVERSION PROCESSES

1.1 Introduction

As part of Task 6.1, a techno-economic analysis is performed to explore the economic feasibility and prospects of the SPOTLIGHT plasmon conversion processes to produce either synthetic methane or CO. In the project, technology is developed in which light is used to drive chemical reactions. The concept is demonstrated for two chemical processes, the Sabatier (or methanation) reaction and the reverse water-gas shift (RWGS) reaction. In both processes, CO_2 and H_2 are used as feedstocks. The Sabatier reaction is an exothermic process (equation 1) in which synthetic methane (CH_4) is produced, while RWGS is endothermic, generates carbon monoxide (CO) and requires heat (equation 2). If the supplied CO_2 and H_2 are both sustainable and only renewable energy is utilized, both processes can contribute in avoiding fossil CO_2 emissions. The origin and sustainability of both CO_2 and H_2 falls outside the scope of this analysis and only their costs are assessed. A life cycle assessment is performed as part of Task 6.3 and provides more detailed information about the prerequisites for the sustainability of both processes.

$$\mathrm{CO_2} + 4H_2 \rightleftharpoons \mathrm{CH_4} + 2\mathrm{H_2O} \quad \Delta H_{298K} = -165.0\ \mathrm{kJ}/mol \quad (1)$$

$$\mathrm{CO_2} + H_2 \rightleftharpoons \mathrm{CO} + \mathrm{H_2O} \quad \Delta H_{298K} = 41.2\ \mathrm{kJ}/mol \quad (2)$$

Previous research has also explored the techno-economic prospects of the sunlight-driven Sabatier and RWGS process, demonstrating their potential competitiveness with conventional production pathways in the future [1] [2] [3]. Here we use the latest experimental data of the validated SPOTLIGHT technology, in the lab and using sunlight (TRL 4-5), and provide a outlook based on an advanced process design.

The SPOTLIGHT technology exists of a borosilicate glass flow plate that contains a catalyst material in ten parallel channels. The catalyst material exists out of Ru on Al_2O_3 for the Sabatier process and out of Au on TiO_2 for RWGS. The reactive gasses (CO_2 and H_2) can flow through the channels, in which the catalyst can be activated by light. Besides the reaction channels, the plate contains some additional channels to allow for heating or cooling. More details about the catalyst design and evaluation have been reported in D4.1-4.4 as part of WP 4 and in literature [2] [3] [4] [5] [6].

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Novel aspects of the photoreactor concept described here, are not only the flow plate but also the integration of an artificial light source for which an LED device has been selected. To validate the implementation of the LED in terms of costs, we performed a techno-economic analysis in which we evaluate and compare three different system configurations: an LED-driven process, an LED and sunlight-driven process, and a sunlight-driven process. We determine the different configurations and their performance based on experimental results. We assess the investment and operational costs of these system configurations when scaled up to a 100 kton production facility, and determine the production costs of the different routes. We also explore the dependency of the production costs on several parameters through a sensitivity analysis.

1.2 System configurations

As previously reported, a process has been designed and simulated in which the photochemical reactor is one of the main technology components [2] [9]. Besides the photoreactor, the balance-of-plant equipment exists of two compressors to deliver to gasses at the correct pressure, a mixer and heat exchanger, a condenser to separate water, and a gas separation step to provide the product at the required purity. The three system configurations differ mainly in their light generation systems (Figure 1). In the LED-driven configuration 1, the LED is the sole primary optics systems, which is placed just ahead of the photoreactor making secondary optics redundant. In configuration 2, the photoreactor is illuminated by either the LED or sunlight. A secondary optics system is included to evenly guide the light, being it either from the sun or the LED, towards the reactor plate. In the experimental setup, the solar furnace at the site of DLR has been used, while we assume for the analysis that a parabolic trough system is used to concentrate the sunlight onto the secondary optics. In the sunlight-driven configuration 3, only the parabolic trough is in place as the primary optics system.

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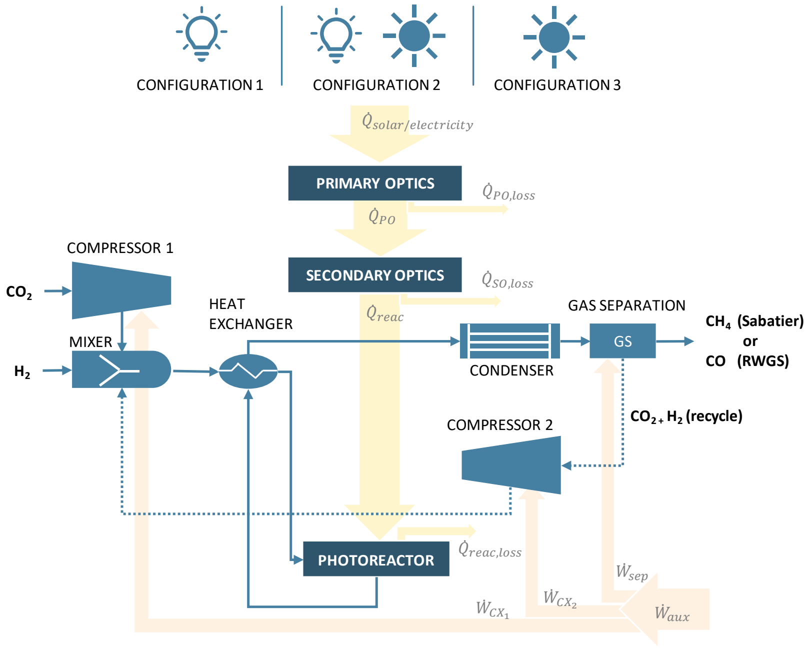

FIGURE 1. SYSTEM CONFIGURATIONS FOR THE TWO PLASMON CONVERSION PROCESS: SABATIER AND RWGS

1.3 Sabatier process based on experimental data

The reactor plate (0.014 m^2) contains, with a catalyst loading of 0.22 kg m^{-2}, 3 g of catalyst material, covering 0.006 m^2 (rest is enforcing/cooling area). The catalyst material for the Sabatier reaction exist of 6% Ru on Al_2O_3. The reaction rate increases when the temperature rises. This is achieved by irradiation of around 162 W_{opt}, which reaches the inside of the plate. Under these conditions, 0.18 mol_{CH4} h^{-1} is produced, which would resemble a production of 23 kg_{CH4} yr^{-1} if operated for 8000 h. The input gas flow is 500 mL min^{-1}, existing out of $N_2/H_2/CO_2$ (1:5:1), or 0.19 mol h^{-1} (CO_2). This results in a carbon conversion efficiency of 94 mol%. If this system is scaled to produce 100 $kton_{CH4}$ yr^{-1} and operates for 8000 h per year, it requires 4.3 million reactor plates, i.e. ~60,000 m^2 of reactor area. These reactor plates exist out of glass, support structure and are filled with the catalyst. Ruthenium (779 kg) is the main cost component (92%) of the photoreactors, which in total cost 13 M€. These costs do not include any plate manufacturing, which for each euro spend per plate will add 4.3 M€ to the total. We here neglect these manufacturing costs but these can be substantially for the current type of plate design. These assumptions are valid for both configuration 1 and 2, in which the process runs for 8000 hours per year. In configuration 3, the system only operates when the sun shines (2100 h yr^{-1}) and nearly four times more reactor area is required to produce the same 100 $kton_{CO}$ yr^{-1}. This results in reactor costs of 50 M€.

Light reaching the reactor plate is kept constant between the different configurations, while the required energy input to generate this light can differ due to losses. In configuration 1, an LED light in installed that directly faces the surface of the reactor plate. Only reflective losses at the surface of the reactor (11%) lower the optical efficiency, while the LED operates at an average electrical efficiency of 50%. This means that 162 W_{opt} of light reaches the inside of the plate (and, thus, the catalyst) of 0.014 m^2, which is 12 kW_{opt} m^{-2}. The electricity input for such an LED amounts to 363 kW_e (or 26 kW_e m^{-2}). The scaled-up system of 100 $kton_{CO}$ yr^{-1} would require 4.3 million SPOTLIGHT LEDs with an input power of 1.6 GW_e. We estimate that the LED equipment incl. installation costs 920 € kW_e^{-1} [10] [11] or approximately 1450 M€ for the entire system, clearly the main cost component of the reactor system.

When next to the LED, a solar concentrator is used to make use sunlight which is free of charge, around 0.23 m^2 of concentrator system (mirror area) per reactor plate is required including optical losses at the concentrator (10%) and within the secondary optics (22% of which half are reflective losses at the plate surface). In total, this would require almost 1.0 million m^2 of mirror area. The costs of mirrors, structure, and electrical tracking system amount to appr. 133 € m^{-2} (based on a parabolic trough system, [12]). Total installed costs of the concentrator system add up to 133 M€ (~10x more than photoreactor costs) for configuration 2. We should note that the costs of the LED system in configuration 2 of around 1650 M€, surpass those of configuration 1 because of additional optical losses (11%) in the secondary optics. When only sunlight is used, configuration 3, the system can only be operated for 2100 full load hours (FLH) and requires nearly four times as many reactor plates (16 million plates, ~570,000 m^2 of plate area), connected to 3.8 million m^2 of mirror area of the solar concentrator system. Such a concentrator system would cost more than 500 M€. Costs for secondary optics (e.g., fluxguide and shutter) are not separately analyzed and assumed to be part of the costs of the concentrator system.

The capacity, costs, and energy consumption of other equipment, such as for mixers, coolers, separation and purification systems, and compressors, are calculated through Aspen simulation software based on the throughput of the process. These costs mainly depend on the costs of the required compressors and relate to the amount of recycled gas. The conversion rate of 94% is relatively high and avoids the use of large compressors and results in compressor costs of 9.9 M€ of a total of 10.3 M€ of other equipment costs. The total costs for other equipment rise to 36 M€ when the process runs for only 2100 FLH, as the capacities increase to handle the gas flows in less time.

On top of the equipment costs, the installation, piping, construction of buildings, etc. at the chemical plant requires additional capital. Typically, a cost factor on top of the equipment costs is applied to account for these costs. We only apply this factor to the other equipment costs. We assume it is not realistic to apply it to the photoreactor costs as these consist

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mainly of the costs of gold. Costs for the solar concentrator include their installation and we assume that the LED system functions as a simple component, which is connected to the reactor plate. For indirect costs, such as engineering, construction, owner's costs, and contingency, a multiplication factor of 1.5 is applied to all direct costs to arrive at the total investment costs.

In Figure 2, we summarize the investment costs for each of the three configurations for a facility of 100 kton$_{CH4}$ yr^{-1}. Configuration 1 (LED) is dominated by the costs of the LED lights and results in more than 2200 M€ of total investment costs. Total capital for the second configuration (LED+SUNLIGHT) is even higher and amounts to 2700 M€. Also here the costs for the LED lights dominate but costs increase further compared to configuration 1 due to a higher installed LED capacity, which is induced by a loss in efficiency and additional solar concentrator equipment. Total investment costs for configuration 3 (SUNLIGHT) are lowest and add up to 1000 M€.

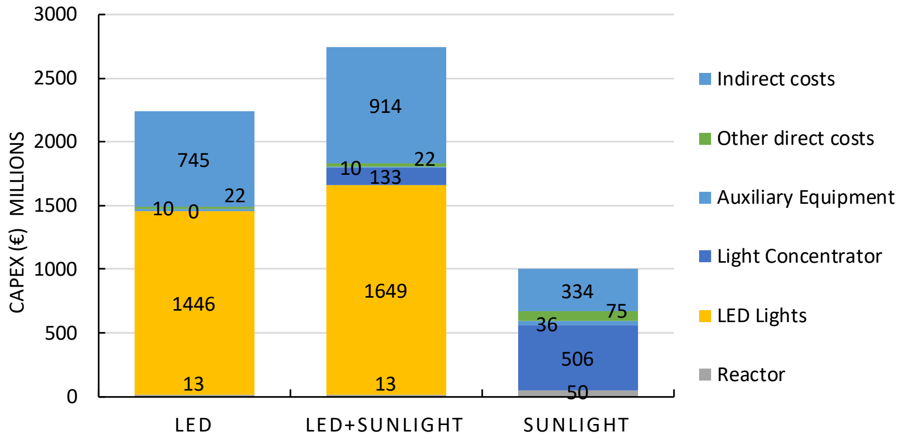

FIGURE 2. INVESTMENT COSTS OF THE EXPERIMENTAL SABATIER CASE SCALED TO A 100 KTON PER YEAR CH_4 PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

The production costs depend on the investment costs and operational costs. For our scaled-up experimental Sabatier setup, total CAPEX amounts to 1.0 to 2.7 billion €. This total is discounted (10% discount rate) over the lifetime of the plant (15 years) and corresponds to 132 to 360 M€ annually. Operational costs exist of costs for feedstocks and electricity and for fixed operational and maintenance (O&M) costs. The process consumes 50 kton of H_2 and 274 kton of CO_2 to produce 100 kton$_{CH4}$ yr^{-1} and an additional 224 kton of water. For a H_2 price of 5 € kg^{-1} and a CO_2 price of 50 € ton^{-1}, feedstock costs amount to 50 M€ for H_2 and 3 M€ for CO_2 for each of the configurations. The electricity consumption is substantially higher for the configurations where LED lights are used: 13 TWh for configuration 1; 11 TWh

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for configuration 2; and only 0.07 TWh for configuration 3. For an electricity price of 50 € MWh^{-1}, this results in annual costs of 632 M€, 533 M€, and 4 M€, resp. A fixed percentage (3%) of the total CAPEX is used to determine the fixed O&M costs. Total production costs for configurations 1-3 amount to 1046, 1028, and 218 € GJ^{-1}, resp. as indicated in Figure 7.

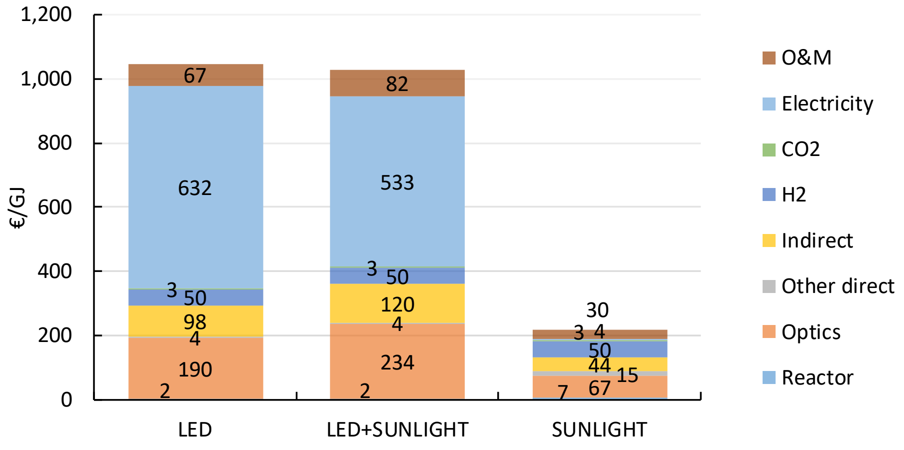

FIGURE 3. CH_4 PRODUCTION COSTS OF THE EXPERIMENTAL SABATIER CASE SCALED TO A PRODUCTION FACILITY OF 100 KTON CH_4 PER YEAR FOR EACH OF THE THREE CONFIGURATIONS

These production costs are at least an order of magnitude higher compared to natural gas prices. In 2021, European natural gas prices were very high but still averaged around 16 € GJ^{-1}. The sunlight-driven process is clearly the lowest in terms of costs among the three configurations, mainly due to high capital costs for the LED system and the high electricity consumption of the LED lights. The process is, however, still at an early development stage and several improvements can be expected to enhance the performance. Below we sketch a more advanced case for the Sabatier process in which several improvements have successfully been realized.

1.4 Advanced Sabatier process

Several improvements can already be foreseen based on the insights obtained from the recently performed SPOTLIGHT experiments. The first aspect is the increase in irradiation on the reactor plate to increase the local temperature and improve the performance of the photochemical reaction. In the glass plate reactor, we observed a rather substantial pressure drop over the catalyst material. We expect that different catalyst particles or reactor channels can reduce this effect and allow for a higher gas throughput. The existing reactor is only 44% effectively filled with catalyst because of the surrounding support channels. An improved reactor design should allow a higher surface coverage of the catalyst. This could directly improve the performance by a factor two, although it doubles the amount of catalyst. Other developments may enhance the reduction of reflective losses to enhance the light efficiency and the improvement of the LED performance to reduce the electricity needs. To explore the effect of this rather straightforward developments, we next present the results of our analysis of such an advanced case for all three configurations.

For the advanced case, the reactor plate, catalyst composition, and inlet pressure are kept the same as for the experimental case. The flow is five times increased, while the carbon conversion rate improves, thanks to the higher light intensity (30 kW_{opt} m^{-2}), to 97%. This results in a production rate of 1.08 mol_{CH4} h^{-1}, which would resemble a production of nearly 140 kg_{CH4} yr^{-1} if operated for 8000 h. For 100 $kton_{CH4}$ yr^{-1}, it requires 0.72 million reactor plates, i.e. ~10,000 m^2 of reactor area. This area is six times smaller compared to the experimental case and has a severe impact on the costs as can be seen in Figure 4. The relative contribution of the system component costs does not significantly shift but overall the total investment costs reduce to 890, 986, and 412 M€ for, respectively, configuration 1 to 3.

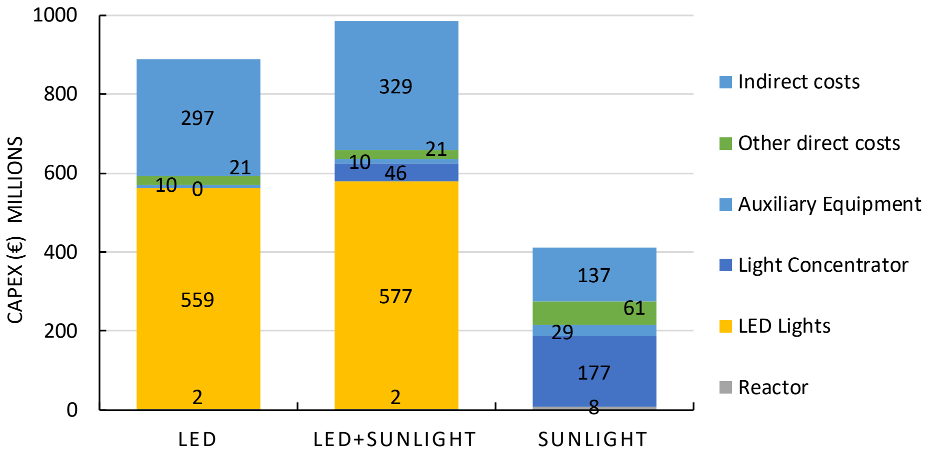

FIGURE 4. INVESTMENT COSTS OF THE ADVANCED SABATIER CASE SCALED TO A 100 KTON PER YEAR CH_4 PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

The production costs for the advanced case are substantially lower compared to the experimental case and amount to 443, 400, and 123 € GJ^{-1} for resp. configuration 1 to 3, as indicated in Figure 5. These production costs are, especially for configuration 1 and 2, higher compared to the fossil benchmark but are roughly two times lower compared the SPOTLIGHT experimental case. This shows that technological developments can have a severe impact on the economic feasibility of the process.

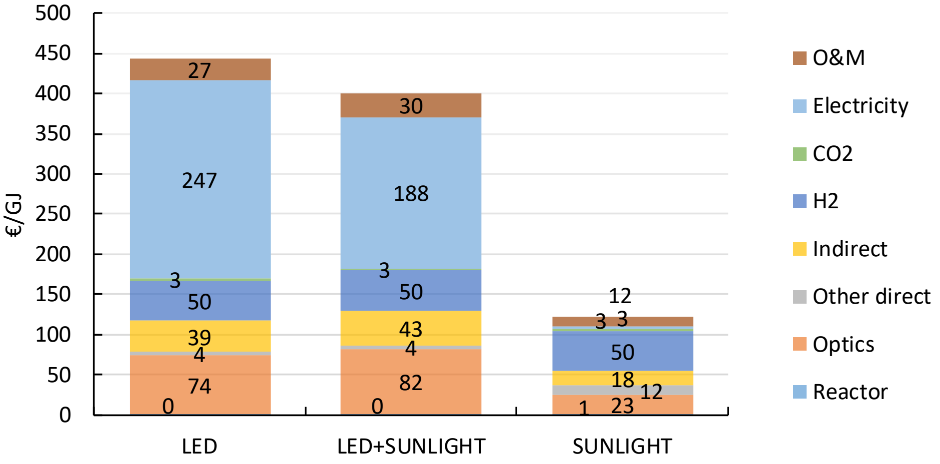

FIGURE 5. CH_4 PRODUCTION COSTS OF THE ADVANCED SABATIER CASE SCALED TO A 100 KTON PER YEAR CH_4 PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

Compared to the fossil benchmark, which is natural gas, it is difficult to compete, even with configuration 3. With high natural gas prices, a carbon tax of still nearly 2000 € ton^{-1} of CO_2 would be required to make the renewable Sabatier route competitive. To become competitive, not only CAPEX should reduce, partly by improving the process efficiency, but also the costs of H_2 should become significantly lower as these contribute 40% to the total.

1.5 RWGS process based on experimental data

The reactor plate in the RWGS process is the same as for Sabatier but the catalyst material differs in that it exists out of 3% Au on TiO_2. The experiment runs at 16 bar inlet pressure at at initially ambient temperature, while the temperature rises upon illumination to approximately 200 °C. Under these conditions, 0.041 mol$_{CO}$ h^{-1} is produced, which would resemble a production of 9 kg$_{CO}$ yr^{-1} if operated for 8000 h. The input gas flow is the same as for Sabatier, 500 mL min^{-1}, but existing out of $N_2/H_2/CO_2$ (1:3:3), or 1.15 mol h^{-1} (H_2/CO_2). This results in a carbon conversion efficiency of 7 mol%. At 8000 h of operation per year, it requires 11 million reactor plates, i.e. ~150,000 m^2 of reactor area, to produce 100 kton$_{CO}$ yr^{-1}. Gold (980 kg) is the main cost component (95%) of the photoreactors, which in total cost 62 M€, excl. manufacturing costs as already mentioned for Sabatier. In configuration 3, the system only operates when the sun shines (2100 h yr^{-1}) and nearly four times more reactor area is required to produce the same 100 kton$_{CO}$ yr^{-1}. This results in reactor costs of 237 M€.

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Similar to Sabatier, the LED operates in the RWGS process at an average electrical efficiency of 50%. Again 162 W_{opt} of light reaches the inside of the plate (and, thus, the catalyst) of 0.014 m^2, which is 12 kW_{opt} m^{-2}. The electricity input for such an LED amounts to 363 kW_e (or 26 kW_e m^{-2}). The scaled-up system of 100 $kton_{CO}$ yr^{-1} would require nearly 11 million SPOTLIGHT LEDs with an input power of 4.9 GW_e. We estimate that the LED equipment incl. installation costs 920 € kW_e^{-1} or 3600 M€ for the entire system, clearly the main cost component of the reactor system.

When next to the LED, a solar concentrator is used to make use sunlight which is free of charge, around 0.23 m^2 of concentrator system (mirror area) per reactor plate is required including optical losses at the concentrator (10%) and within the secondary optics (22% of which half are reflective losses at the plate surface). In total, this would require more than 2.5 million m^2 of mirror area. The costs of mirrors, structure, and electrical tracking system amount to appr. 133 € m^{-2} (based on a parabolic trough system). Total installed costs of the concentrator system add up to nearly 334 M€ (~6x more than photoreactor costs) for configuration 2. We should note that the costs of the LED system in configuration 2 of 4100 M€, surpass those of configuration 1 because of additional optical losses (11%) in the secondary optics. When only sunlight is used, configuration 3, the system can only be operated for 2100 full load hours (FLH) and produces 2.4 kg_{CO} yr^{-1}. To produce 100 $kton_{CO}$ yr^{-1}, 41 million reactor plates (~570,000 m^2 of plate area) are required, connected to almost 10 million m^2 of mirror area of the solar concentrator system. This primary optics system would cost 1272 M€. Costs for secondary optics (e.g., fluxguide and shutter) are not separately analyzed and assumed to be part of the costs of the concentrator system.

The capacity, costs, and energy consumption of other equipment, such as for mixers, coolers, separation and purification systems, and compressors, are calculated through Aspen simulation software based on the throughput of the process. These costs mainly depend on the costs of the required compressors and relate to the amount of recycled gas. The conversion efficiency of 7% results in a relatively large flow of recycled gas. This requires relatively large compressors and results in compressor costs of 18.8 M€ of a total of 19.5 M€ of other equipment costs. The total costs for other equipment rise to 56 M€ when the process runs for only 2100 FLH, as the capacities increase to handle the gas flows in less time.

For indirect costs, such as engineering, construction, owner's costs, and contingency, the same multiplication factor of 1.5 as for the Sabatier process is applied to all direct costs to arrive at the total investment costs.

In Figure 6 we summarize the investment costs for each of the three configurations for a facility of 100 $kton_{CO}$ yr^{-1}. Configuration 1 (LED) is dominated by the costs of the LED lights

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and results in more than 5600 M€ of total investment costs. Total capital for the second configuration (LED+SUNLIGHT) amounts to 6900 M€. Also here the costs for the LED lights dominate but costs increase further compared to configuration 1 due to a higher installed LED capacity induced by a loss in efficiency and additional solar concentrator equipment. Total investment costs for configuration 3 (SUNLIGHT) are lowest and add up to 2500 M€.

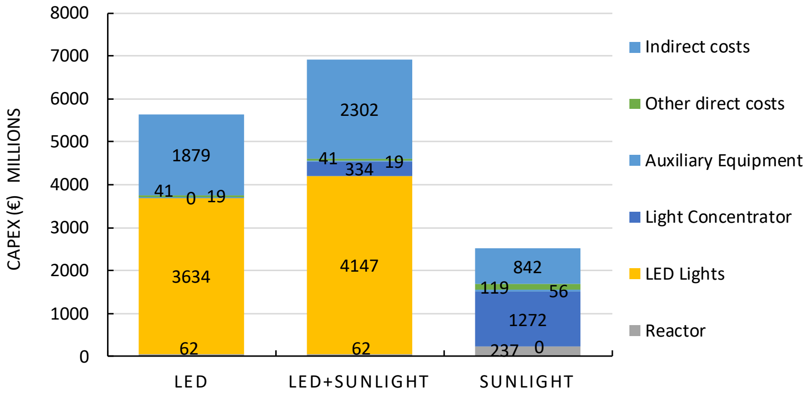

FIGURE 6. INVESTMENT COSTS OF THE EXPERIMENTAL RWGS CASE SCALED TO A 100 KTON PER YEAR CO PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

The production costs depend on the investment costs and operational costs. For our scaled-up experimental setup, total CAPEX amounts to 2.5 to 6.9 billion €. This total is discounted (10% discount rate) over the lifetime of the plant (15 years) and corresponds to 332 to 908 M€ annually. Operational costs exist of costs for feedstocks and electricity and for fixed operational and maintenance (O&M) costs. To produce 100 kton_{CO} yr^{-1}, the process consumes 7 kton of H_2 and 185 kton of CO_2. Next to the product, also 68 kton of water is generated and 28 kton of CO_2 ends up in the water fraction and is wasted. We assume that these byproducts contain no value. For a H_2 price of 5 € kg^{-1} and a CO_2 price of 50 € ton^{-1}, feedstock costs amount to 36 M€ for H_2 and 9 M€ for CO_2 for each of the configurations. The electricity consumption does vary and is substantially higher for the configurations where LED lights are used: 32 TWh for configuration 1; 26 TWh for configuration 2; and only 0.05 TWh for configuration 3. For an electricity price of 50 € MWh^{-1}, this results in annual costs of 1589 M€, 1339 M€, and 2 M€, resp. A fixed percentage (3%) of the total CAPEX is used to determine the fixed O&M costs. Total production costs for configurations 1-3 amount to 2544, 2499, and 455 € GJ^{-1}, resp. as indicated in Figure 7.

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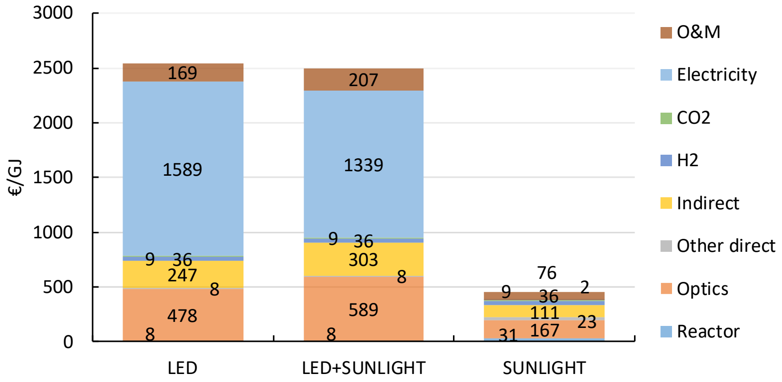

FIGURE 7. CO PRODUCTION COSTS OF THE EXPERIMENTAL RWGS CASE SCALED TO A 100 KTON PER YEAR CO PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

We should note that these costs are substantially higher compared to fossil-based routes, which cost around 17 € GJ^{-1} or up to around 100 € GJ^{-1} at a fossil carbon price of 200 € ton^{-1}. Additionally, billions of capital requirement for a chemical plant of this size is high and unlikely to become financed. These results can partly be explained by the poor energy efficiency of the processes, which increases the capacity of installed equipment to supply enough light. The total energy efficiency (energy of CO/energy input (light/electricity/H_2)) amounts to around 0.9% for both configuration 1 and 2 and 1.4% for configuration 3. This indicates that the current experimental setup should be improved to demonstrate the economic feasibility of the photochemical process.

1.6 Advanced RWGS process

As explained for the Sabatier case, several improvements are foreseen based on the insights of the SPOTLIGHT project. To explore the effect of these developments, we present the results of our analysis of such an advanced case for all three configurations in the next section.

For the advanced case, the reactor plate, catalyst composition, and inlet pressure are kept the same as for the experimental case. The flow is five times increased, while the carbon conversion rate improves, thanks to the higher light intensity (30 kW_{opt} m^{-2}), to 12%. The overall energy efficiency of the process improved to 4.2%, 4.6%, and 5.9% for configuration 1-3, resp. This results in a production rate of 0.40 mol_{CO} h^{-1}, which would resemble a production of 90 kg_{CO} yr^{-1} if operated for 8000 h. If this system is scaled to produce 100 $kton_{CO}$ yr^{-1} and operates for 8000 h per year, it requires 1.1 million reactor plates, i.e. ~15,000 m^2 of reactor area. This area is nearly an order of magnitude smaller compared to the experimental case and has a dramatic impact on the costs as can be seen in Figure 8. The

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relative contribution of the system component costs does not significantly shift but overall the total investment costs reduce to 1133, 1275, and 606 M€ for, respectively, configuration 1 to 3.

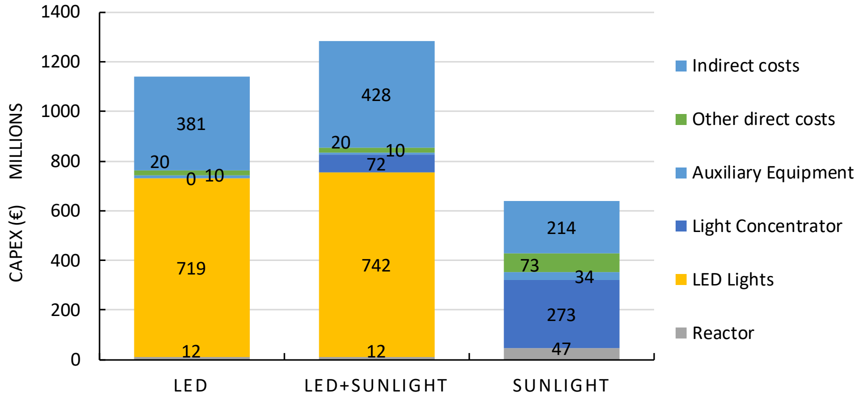

FIGURE 8. INVESTMENT COSTS OF THE ADVANCED RWGS CASE SCALED TO A 100 KTON PER YEAR CO PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

Assessing the production costs for the advanced case indicates that these substantially reduced to 548, 496, and 154 € GJ^{-1} for resp. configuration 1 to 3, as indicated in Figure 9. These production costs are, especially for configuration 1 and 2, higher compared to the fossil benchmark but are already 4-5 times lower compared the SPOTLIGHT state-of-the-art. This shows that technological developments can have a severe impact on the economic feasibility of the process.

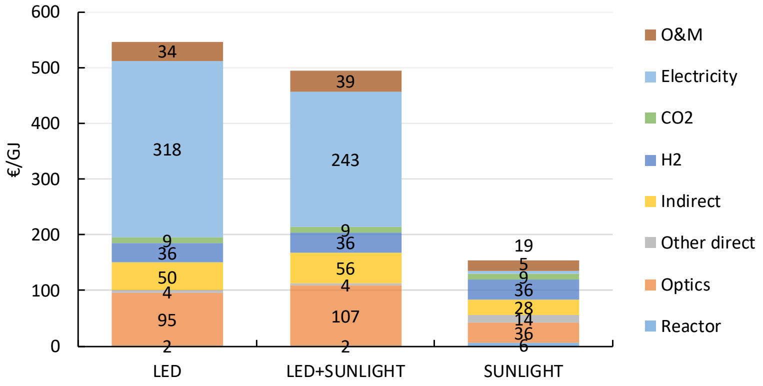

FIGURE 9. CO PRODUCTION COSTS OF THE ADVANCED RWGS CASE SCALED TO A 100 KTON PER YEAR CO PRODUCTION FACILITY FOR EACH OF THE THREE CONFIGURATIONS

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For the three configurations in the advanced case, sensitivity analysis indicates which of the parameters affects the largest influence on the production costs (). From all these results can be concluded that the LED lights are an important cost component to the overall costs, both in terms of capital costs and electricity use. Only when the costs of the LED system reduce and the LED efficiency can further improve, the advantage of operating 8000 FLH thanks to artificial lighting can also become economically beneficial. Notably, a full continuous operation does pose other benefits and is likely less demanding for the balance-of-plant operation. These system aspects have barely been explored in the SPOTLIGHT project and it is, for instance, recommended to investigate also the impact of flexible operation on the compression, storage, and purification equipment in the process.

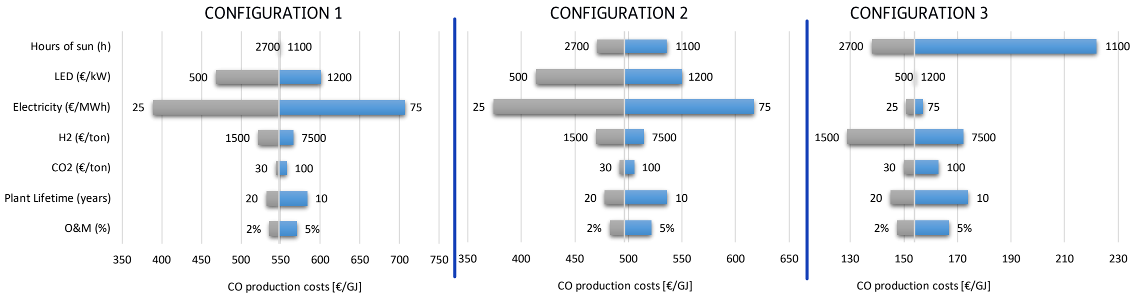

FIGURE 10. PRODUCTION COSTS SENSITIVITY ANALYSIS OF THE ADVANCED CASE FOR ALL THREE CONFIGURATIONS

The fossil benchmark price amounts to around 17 € GJ^{-1} and shows that none of the renewable RWGS routes is competitive. With high natural gas prices, a carbon tax of around 500 € ton^{-1} of CO_2 would be required to make the renewable RWGS advanced case configuration 3 competitive.

1.6.1 Development outlook

Many aspects in the analysis contain a high level of uncertainty and in the following section is explained how further developments can affect the outcome of the techno-economics and under what circumstances an LED-driven process could become cost-competitive with the sunlight-only configuration.

Compared with previous work [2], the process conditions and assumptions of this techno-economic assessment are slightly altered, leading to different results. In earlier experiments, the conversion has been kept low (1%) at a high flow rate for study purposes, while we assumed for the base case calculations that the flow was lower and the conversion higher (10%) at 14 kW m^{-2}. Such a configuration resulted in an energy efficiency of 4% and production costs of 205 € GJ^{-1}, compared to 1% and 455 € GJ^{-1} for configuration 3 in our experimental case. In a further developed case [2], the irradiation, flow and conversion were increased to 25 kW m^{-2}, 5 L min^{-1}, and 18%, resp., and resulted in an energy efficiency of 46% and production costs of 53 € GJ^{-1}. In the advanced case presented here in section 1.6, the performance improvements are less optimistic and result in an energy efficiency of 6%, and, not unexpectedly, higher production costs, namely 154 € GJ^{-1}.

When we also apply more optimistic development parameters in the current assessment, costs, not surprisingly, reduce further for all configurations. More interesting would be to understand under what circumstances, the LED-integrated configurations become cost-competitive with the sunlight-driven configuration. The developments should be significant to deal with the rather substantial cost-gap when we compare configuration 1 and 2 with 3. An advantage of the LED system is that a higher optical power can possibly be generated without a drastic increase in costs. If the LED can produce an optical output in the reactor of 30 kW/m^2 and can operate at a very high efficiency (~95%) by both improved diode efficiency and heat integration, the reaction temperature will be raised. As a result, we expect that the conversion efficiency increases as well as the reaction rate, similar to the assumptions in the previously reported developed case [2]. Supposed that with the same catalyst loading per m^2 of reactor a higher throughput and yield can be achieved, the overall production costs decline substantially.

If we fix the conversion efficiency at 18%, at an optical power of 30 kW m^{-2} and with a input gas flowrate of 5 L min^{-1}, the total production per reactor, if operated for 8000 h, equals 270 kg_{CO} yr^{-1}: thirty times more as in our experimental case. This would improve the overall energy efficiency to 16% (for all configurations, for LED efficiency of 90%), which is a substantial increase compared to the experimental and advanced cases (1 and 4%) but not yet as high as the previously reported developed case (46%). When equipment costs and LED efficiency remain the same as earlier described in the advanced case, the production costs of the LED-driven configurations are still more than twice as expensive compared to configuration 3 (left bar versus right bar in Figure 11). Further improvements, i.e., LED efficiency (from 60 to 95%), lower LED costs (80% reduction), and lower electricity costs (from 50 to 20 € MWh^{-1}), as presented in Figure 11 can eventually result in break-even costs between the three configurations. Such an overall improved performance would also result in a more competitive case of the renewable routes compared to the fossil benchmark and a carbon tax of around 300 € ton^{-1} of CO_2 would be sufficient to reach break-even with the fossil price.

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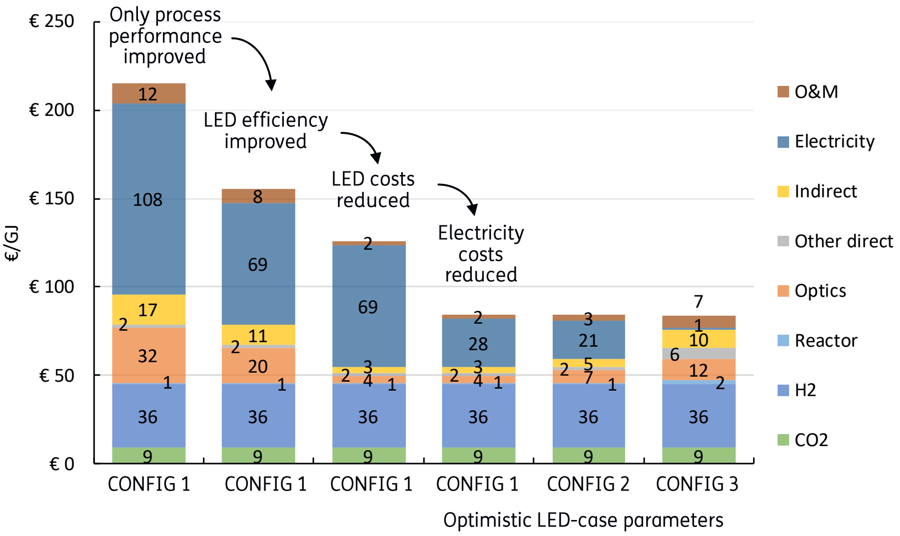

FIGURE 11. PRODUCTION COSTS OF THE THREE RWGS CONFIGURATIONS BASED ON OPTIMISTIC DEVELOPMENT PARAMETERS

These results indicate that only when the performance improves, LED lights can reduce substantially in costs and electricity costs are low, the LED-based configurations can become cost competitive with the sunlight-driven case. Other effects, however, such as operational stability and (intermediate) storage requirements are not explored and can have an effect on the cost performance of all configurations but likely induce a more negative impact on configuration 3. We recommend to further explore the influence of such effects, which are especially relevant if the RWGS process will be combined with a follow-up process, such as methanol or Fischer-Tropsch synthesis. Additionally, it seems worthwhile to investigate if the photoreactor concept, either with or without LED system, can be applied to different types of chemical reactions as these may benefit more from the optical energy or may lead to products of higher value.

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CONCLUSIONS

In this techno-economic analysis we illustrate that the plasmon conversion processes developed in the SPOTLIGHT project are currently highly capital intensive. Especially the LED-based configurations suffer from high LED costs and in combination with a high and expensive electricity consumption, these routes can, based on this analysis, not compete with the solely sunlight-driven processes. We also show that further developments may substantially improve the performance of the process, both for Sabatier and for RWGS. Effects are largest for RWGS because of the relatively low conversion and throughput that was obtained during the experimental campaign.

For Sabatier, the advanced case of the sunlight-driven configuration 3 shows the most promise and can reach CH_4 production costs of 123 € GJ^{-1}. Compared to the fossil benchmark, which is natural gas, it is difficult to compete, and only with a carbon tax of around 2000 € ton^{-1} of CO_2 the renewable Sabatier route can become competitive. Even when capital costs can be further reduced, the process relies significantly on the H_2 feedstock costs as these contribute around 40% to the total. Lower green hydrogen prices are therefore also essential to reach competitiveness with carbon-taxed natural gas prices.

Similar to Sabatier, also for RWGS the advanced case configuration 3 shows the most promise and can reach CO production costs of 154 € GJ^{-1}. This route can reach break-even costs with the fossil benchmark price in combination with a carbon tax of around 500 € ton^{-1} of CO_2. As H_2 and CO_2 as feedstocks together contribute for almost 30%, a change in their feedstock price may have a substantial effect on the production costs.

Only when the performance can be even further improved and LED lights and electricity can reduce substantially in costs, the LED-based configurations can become cost competitive with the sunlight-driven case. Under these circumstances, a carbon tax of around 300 € ton^{-1} of CO_2 would be sufficient to reach break-even with the fossil price. We recommend to further explore the influence of other effects on the process, such as flexible operation and storage, and investigate potential integration with a follow-up syngas conversion route. Also, the application of similar plasmon conversion processes, either with or without LED system, in different types of chemical reactions can be of research interest.

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