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A realistic future of solar fuels

Assessing possibilities of solar liquid hydrocarbon fuels via photovoltaics and electrolysis and their potential application in the transportation sector

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Abstract

This paper presents an overview of the opportunities for liquid solar fuels (LSF). The production of LSF via PV, electrolysis, direct air capture (DAC), CO2 activation and Fischer-Tropsch (FT) synthesis was analysed. After literature review of the current state of the art in terms of efficiency and costs of LSF, the maturity of the five components of the PV-electrolysis pathway was assessed via technological readiness assessment (TRA). TRA results show how FT, PV and AE have received TRL 9 and should mainly be developed further by cost reductions. DAC was estimated at TRL 7, providing plans for integration in the solar fuel cycle on short-term. The overall maturity is limited by CO2-reduction via a reverse water-shift gas reaction, however, as this technique is still in need of research for suitable catalysts and integration strategies, it reduces reducing the final TRL for LSF to 5 out of 9. Afterwards, solar fuel options for implementation in the aviation sector were discussed. Typically, biofuels are preferred as fuel option, yet LSF brings additional advantages in terms of scalability and environmental problems. In general, when efficiency improvements and cost reduction persevere, future implementation of solar fuels might be a reality. Therefore, this paper also suggest further consideration of solar fuel options in aviation specifically.

List of abbreviations

AE = Alkaline electrolysis

Bbl = Barrel (volume unit for liquid fuels)

DAC = Direct air capture

FT = Fischer-Tropsch

LSF = Liquid solar fuels

PEC = Photo-electrochemical

PEM = Polymer electrolyte membrane

PTL = Power-to-liquid

PV = Photovoltaics

R&D = Research and development

RE = Renewable energy

RWGS = Reverse water-gas shift

STH = Solar-to-hydrogen

STL = Solar-to-liquid

STF = Solar-to-fuel

TRA = Technology readiness assessment

TRL = Technology readiness levels

Introduction

Background

The current global energy transition towards renewable energy systems is characterized by an increasing share of renewable energy since 2000. Currently, 26% of the mondial electricity share is renewable (IEA, 2019). Renewable electricity generated by PV is an important component of renewable energy production. Recent developments of solar PV are paired with improving cost reductions in the 21st century, which are expected to continue with increasing possibilities of competitiveness (Detz, Reek, & van der Zwaan, 2018). Furthermore, of the existing renewable technologies today, solar PV is expected to account for 60% of overall renewable energy capacity growth until 2024 (IEA, 2019).

The future potential of harvesting solar energy is easily sufficient to replace fossil energy; merely one hour of solar radiation roughly equals the current mondial energy consumption (Heeger, 2012; Styring, 2012). In general, as clearly abundant energy source with major energy potential, the sun will undeniably play a key role in replacing conventional energy sources for pathways towards reduction of carbon dioxide emissions. In other words, significant contributions of PV in future energy scenarios simply cannot be questioned (Centi & Perathoner, 2010; Kraan, Kramer, Haigh, & Laurens, 2019).

Problem description

Solar energy is, however, typically purely inclined towards electricity generation (Tuller, 2017). While development of photo-voltaic electricity looks promising, currently still approximately a third of primary energy consumption involves electricity use; the residual share is dominated by fossil fuels for heating and transportation purposes (Goede, 2018; Tuller, 2017). Meanwhile, combining the potential of the sun with efficiently storing solar energy has proven to be problematic. PV cannot provide constant supply, typically leading to electricity surpluses during the day and shortages at night, which must be levelled to increase reliability and meet consumer demand (Goede, 2018). Therefore, as for all intermittent energy sources, efficient storage forms the greatest challenge for PV (Heeger, 2012).

Typical disadvantages of solar PV are augmented by characteristics of the transport sector, where fossil fuel dependency is evident. Fossil fuels – mainly oil and natural gas – make up 96% of this sector's energy consumption, while the remaining 4% is covered by electricity mostly generated by fossil fuels (Tuller, 2017). Aviation is even estimated to be 99.99% dependent on petroleum based fuels (Trieb, Moser, & Kern, 2018). For transportation, electricity, hydrogen, biofuels and synthetic fuels have been suggested as realistic alternatives for petroleum products (Barrett, 2011). Electrification in the transport sector to reduce greenhouse gas emissions is prioritized (Tuller, 2017). However, even with maximized electrification strategies, hydrocarbon demand will continue to persist (Kraan et al., 2019). While Detz et al. (2018) argue that electrification for light transport is ongoing, they expect heavy transport and aviation to pose significantly more problems.

To solve this, instead of solely replacing the current fuels with alternatives, possibilities of carbon neutral should be developed and researched simulatanously as part of governmental ways to sustainability. One way of achieving this is by converting solar energy into the liquid hydrocarbons abundantly used today; this is the general core of the solar fuel concept.

Research questions

This research project will elaborate on solar fuel production, its key characteristics and explore possible applications for usage as transportation fuels. The following research question has been proposed:

To what extent are PV-electrolysis based hydrocarbons 'ready' for future applications in transportation?

Additionally, three subquestions highlight the production process of solar fuels, its key challenges and possible future strategies, more specified within the research scope:

1. What technological and economic challenges does production of solar based liquid hydrocarbons bring?
2. To what extent are solar fuels technologically matured?
3. How can solar fuel subsequently be applied in the future energy system for transportation?

The objective of the research is to present an overview of the current state of solar fuel development and consequently enabling the theoretical findings to be implemented in further specified applications. Interpreting the findings of this paper could possibly enable further research about solar fuels in more detailed environments.

Theory

In this chapter, key characteristics of solar fuel production are briefly provided first to clarify the context of the proposed research.

Solar fuel: definition and pathways

As Trieb et al. (2018) illustrate in figure 1, we distinguish many different ways of liquid hydrocarbon synthesis. Solar fuels generally refer to processes which convert solar energy into stored chemical energy (Haije & Geerlings, 2011; Styring, 2012). As figure 1 shows, hydrocarbon fuels can be synthesised with a variety of feedstocks and techniques. For solar fuels, the final energy carriers are equal to conventional fuel production, yet the crucial difference is a production restricted to solar energy only.

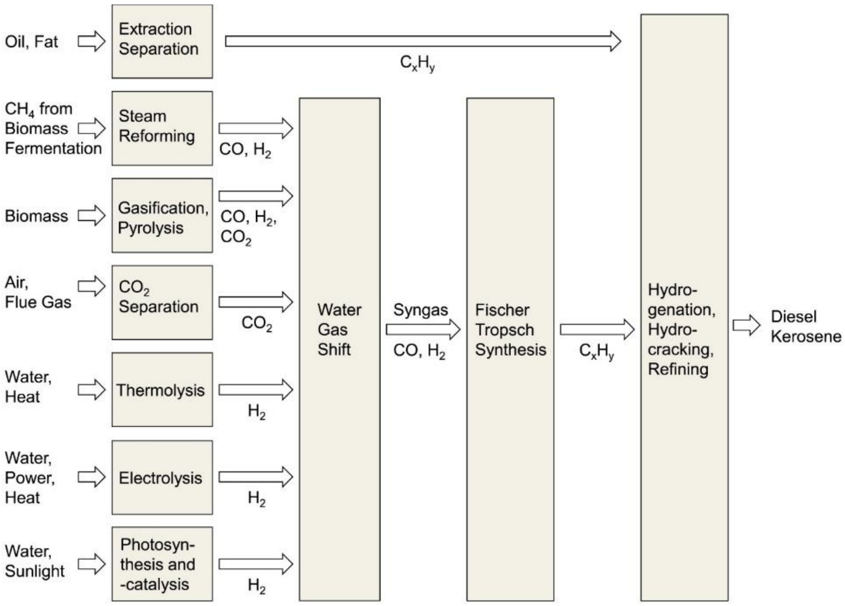


Figure 1. Possible synthesis options for liquid hydrocarbon fuels (Trieb et al., 2018)

Generally, two important solar fuels are distinguished, namely (1) hydrogen directly used as fuel and (2) hydrocarbons (e.g. diesel or kerosene) produced with solar hydrogen (Heeger, 2012). Additionally, Centi & Perathoner (2010) note that both electrical energy (although technically not classified as fuel) and biofuels (as their usage of photosynthesis on which the solar fuel's 'artificial photosynthesis' – often used terminology within solar fuel literature – is based) are often considered solar fuels as well. Therefore, clarification of a proposed solar fuel definition may be needed for this research project to avoid misunderstandings.

For instance, AP can be used as overarching term for solar-to-fuel conversion routes, yet Detz et al. (2018) consider electroconversion of RE into renewable fuels, the focus of this paper, a different category than AP conversion routes. Furthermore, Styring (2012) defines both AP and the artificial leaf as synonyms for solar fuels, while it could be argued that AP is less specific, simply referring to the process of converting solar energy, CO2 and water into fuels, whereas the artificial leaf is defined as a specific application of AP, successfully mimicking natural photosynthesis via different conversion techniques than the ones covered in this paper. Simultaneously, the potential of micro-organisms to provide useful feedstocks for solar fuels via natural photosynthesis is also of scientific interest. This paper, however, only focuses on electrochemical water splitting, which is specified into photoelectrochemical (PEC) devices directly converting the received solar energy and the PV-electrolysis route, which combines the electrolysis with connected PV panels (Montoya et al., 2016); this paper focuses on the latter category.

The decision to focus on PV and electrolysis arises from the claim by Harry Tuller that: “of the three approaches listed here, only the first (PV and electrolysis cells) can rely on infrastructure that is already installed today at a scale that would have the potential to significantly affect current energy needs” and that “the photoelectrochemical and photothermal approaches (…) require considerable development before moving from the laboratory into pilot scale and commercially viable assemblies” (2017, p.4).

Solar fuel production

Solar fuel production via PV-electrolysis requires water, solar energy and CO_2 as primary components (Herron, Kim, Upadhye, Huber, & Maravelias, 2015). Kraan et al. (2019) present 5 key elements for this particular solar fuel production process, visualised in figure 2: solar PV, direct air capturing of CO2 (DAC), CO2 activation into CO, electrolysis and final fuel synthesis.

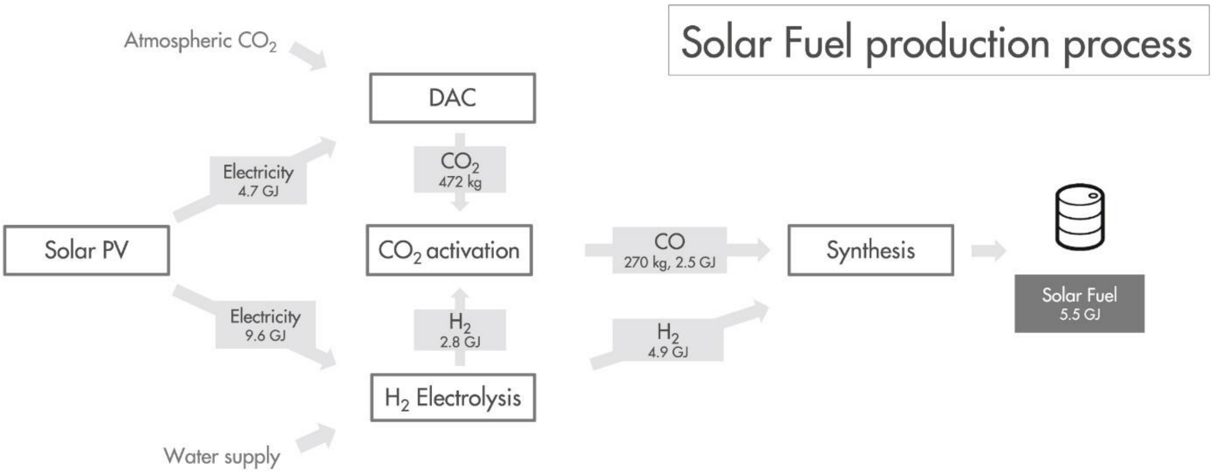


Figure 2. Solar fuel production process (Kraan et al., 2019)

Solar PV provides electricity, enabling carbon neutral fuel production by avoiding additional CO_2 emissions of conventional electricity production. The electricity is used to provide energy for DAC and split water into H_2 and O_2 (i.e. electrolysis). The H_2 and captured CO_2 enable CO_2 activation in a RWGS reaction (Haije & Geerlings, 2011): $CO_2 + H_2 \rightarrow CO + H_2O$. Finally, the obtained mixture of carbon monoxide and hydrogen, often called synthesis gas or syngas, reacts in a FT process into desired hydrocarbon fuels (Trieb et al., 2018).

More detailed techniques and possibilities for each step in the process outline above have been visualized by Herron et al. (2015) in figure 3. As the figure shows, solar heat and photon-based applications are also promising alternatives for solar refineries, yet these methods are outside the scope of this paper. For the remainder of this paper, figure 2 will serve as baseline, providing the components of the pathway which need further analysis.

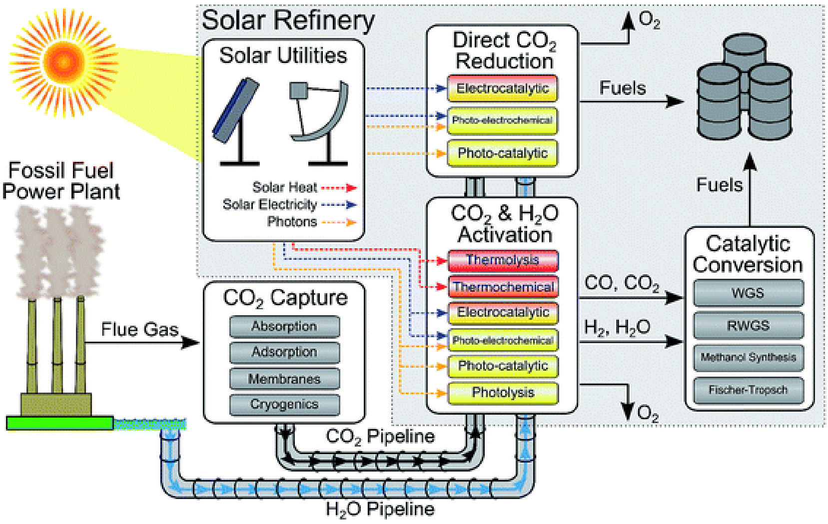


Figure 3. 'Solar refinery' possiblities (Herron et al., 2015)

Hydrogen as solar fuel

Figures 1-3 indicate the crucial role of hydrogen in syngas for eventual hydrocarbon synthesis. Because hydrogen is obtained here using solar power and is widely applicable as fuel, hydrogen is often considered as the most basic solar fuel (Tuller, 2017). In fact, it can be the ideal solar fuel to reduce carbon emissions, as it does not contain carbon at all (Kraan et al., 2019).

Nevertheless, crucial disadvantages of hydrogen are a low energy density per unit of volume and especially complicated storage and transport (Detz et al., 2018; Goede, 2012). While hydrogen will likely play a key role in replacing fossil fuels for hydrocarbon production, it will be restricted by infrastructural challenges (Kraan et al., 2019; Trieb et al., 2018). As hydrocarbons can cope better with these problems, converting hydrogen into liquid hydrocarbons is a preferred solar fuel option for the time being (Haije & Geerlings, 2011).

However, academic literature is often aimed towards solar hydrogen as solar fuel. The transition towards a sustainable hydrogen-based economy has received more attention and brings forth a new discussion about reducing fossil fuels via hydrogen particularly. This could be relevant for transportation, where hydrogen applications are slowly starting to take off. As this paper attempts to assess the complete solar fuel production process – thus including the conversion of hydrogen into hydrocarbons – before looking at transportation, hydrogen will not be considered as independent solar fuel in this project. However, hydrogen *will* be considered as conditional renewable component for producing solar fuel hydrocarbons. A similar approach has been used by Centi & Perathoner (2010), who analysed hydrogen solely as feedstock for production of more suitable carbon based solar fuels.

Methods

In this section, research methodology will be briefly discussed. The conducted research consists of three main stages: literature review, TRA, and exploring solar fuels for aviation.

Literature review

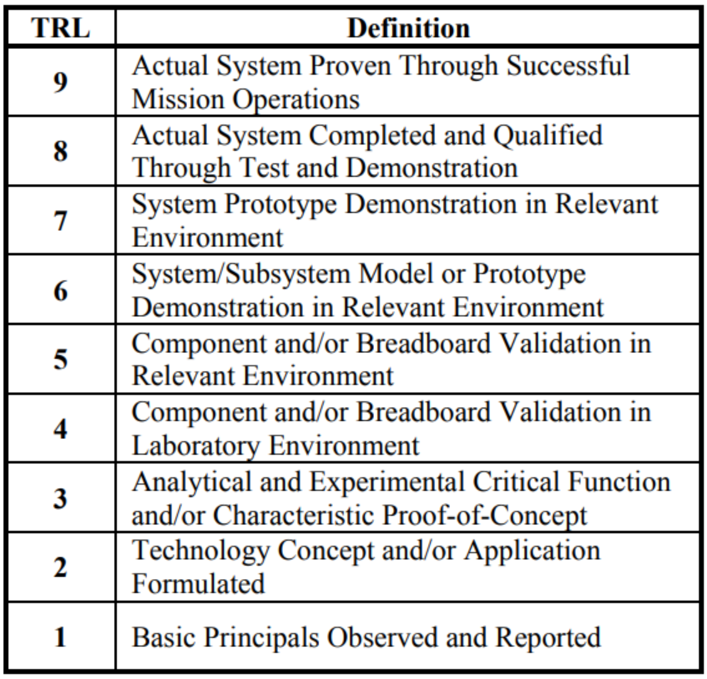
Throughout the initial stage of the research project, data about the solar fuel production process will be collected and consequently analysed via literature review. The literature corpus will consist mostly of peer-reviewed literature which provides information about solar fuel appliances in different contexts, its key challenges and future possibilities.

The initial focus will be on technological and economic challenges of solar fuel production. For addressing technological challenges, a suitable method is a technology assessment (TA), defined as "a form of policy research that examines short- and long-term consequences (for example, societal, economic, ethical, legal) of the application of technology" (Banta, 2009, p.1). As Banta argues that this definition is still broad, TA should ideally be specified first. Likewise, for economic challenges, a general cost-benefit analysis (CBA) to assign monetary values to the relevant technology is a suitable option.

Technology readiness level

Alternatively, analysing the state of a certain technology could be done by usage of the concept of technological readiness levels (TRL). John C. Mankins (1995) presents TRL as a measure to quantify and compare the 'maturity' of technologies. TRL is based on a 9-level scale which indicates the current stage of the analysed technology. Overall definitions of all TRLs are summarized by Sauser, Verma, Ramirez-Marquez, & Gove (2006) in table 1 below.

Table 1: TRL level summary (Sauser et al., 2006)



TRL	Definition
9	Actual System Proven Through Successful Mission Operations
8	Actual System Completed and Qualified Through Test and Demonstration
7	System Prototype Demonstration in Relevant Environment
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment
5	Component and/or Breadboard Validation in Relevant Environment
4	Component and/or Breadboard Validation in Laboratory Environment
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
2	Technology Concept and/or Application Formulated
1	Basic Principals Observed and Reported

In addition to the 9-level scale, TRLs are often separated into three phases, namely predominantly research (corresponding to TRL 1-3), development and demonstration (TRL 4-6) and upscaling towards final commercialization (TRL 7-9 with TRL 9 as a realised commercial full system), summarized in figure 4 below.

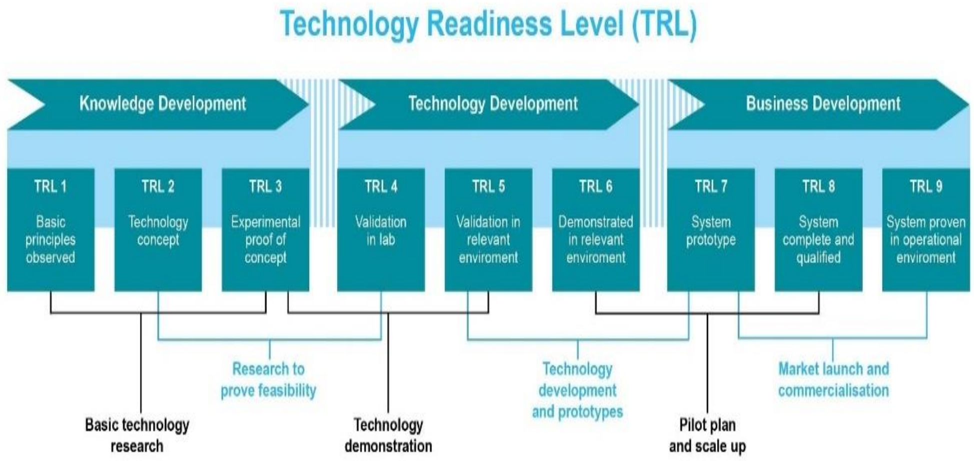


Figure 4: TRL Scale (TU Delft, n.d.-a)

Technology readiness assessment

In conclusion, a relevant analysis using TRL can combine the individual processes of solar fuel production – which may differ from each other significantly – into one suitable assessment. Attempting to interpret the potential of the entire solar fuel production process by analysing individual components on a TRL scale will likely give valuable information about its current state and future possibilities. Suitable assessment using the TRL metric can be conducted via technological readiness assessment (TRA). Detailed guidelines for TRA are provided in the 2009 ESA handbook, which expands initial TRL summaries with extended definitions and individual TRL characteristics. Additionally, four unique checking questions have been set per TRL, which should all be answered affirmatively to reach the relevant readiness level. All TRA questions are listed entirely in appendix I. The five key processes of solar fuel production identified in the theory section of this paper are assessed via this procedure.

Aviation

Afterwards, the TRL findings will be combined with an analysis of more practical possibilities. As stated in the introduction, the aviation sector is dealing with high fossil fuel dependency and considerable difficulty to implement hydrogen and electricity as alternatives for fuels. Furthermore, the aviation is traditionally a powerful and important sector, Hence, this section looks into possible policies, scenarios and strategies for reducing emissions via solar fuels in the aviation sector specifically as LSF may be considered earlier due to the characteristics of the sector mentioned here, combine with the significant emissions and general societal interest for this type of transportation.

In conclusion, the methodology of the research has been visualised in figure 5.

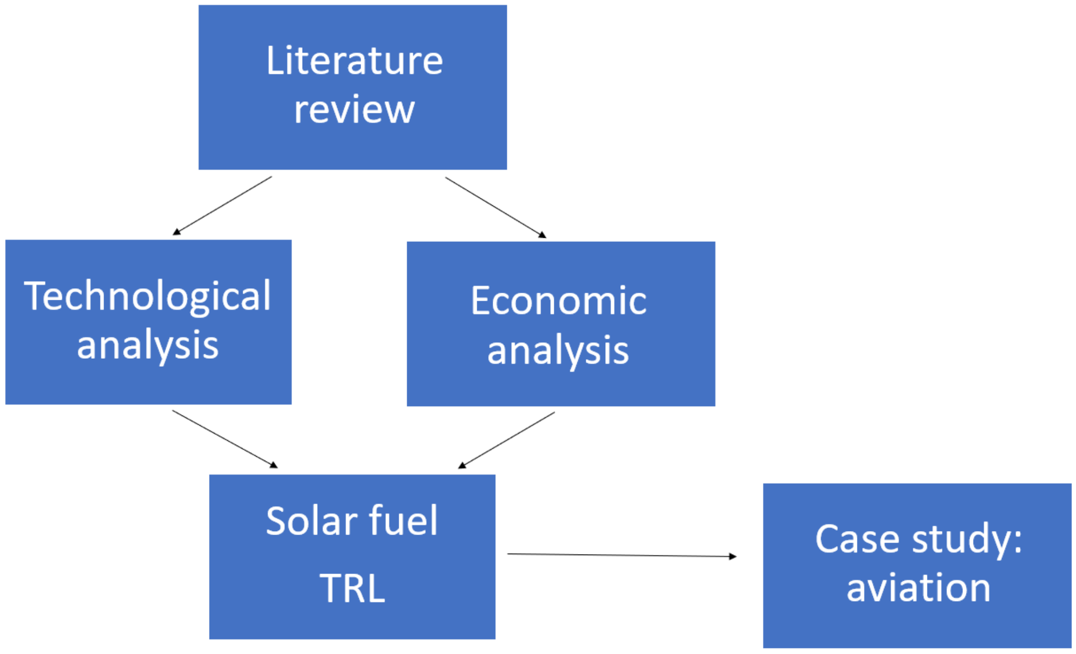


Figure 5. Proposed methodology overview

Results

For the 5 selected subprocesses of solar fuel production of hydrocarbons via PV-electrolysis, key challenges have been analysed first. Consequently, final TRA ratings are discussed. Finally, solar fuel aviation options are analysed.

Analysis of key challenges

Generally, solar fuels include characteristics which are suitable for future implementation at first sight. An important factor is that the process listed above does in principle not require additional techniques but can rely on already existing techniques (Kraan et al., 2019). For example, electrolysis and FT synthesis have been around for 100 years (Goede, 2012), both currently used commercially for conventional fuel production or – in the case of hydrogen production – as important feedstock for fertilizers and plastic products (Heeger, 2012).

Therefore, the main challenges of solar fuel production continue to be improving overall efficiency of this process and above all, further reduction of production costs, as renewable production of hydrogen alone is 4 times as expensive as current 'grey' hydrogen production; similarly, full renewable pathways for solar hydrocarbons are still significantly more expensive than fossil fuel alternatives (Detz et al., 2017).

Efficiency

The concept of conversion efficiency can lead to confusion when comparing different systems for solar fuels, as multiple calculations are possible and many processes can influence the total efficiency. Furthermore, there are a lot of additional factors considered into the overall suitability of a system, which means that a high conversion efficiency can be paired with difficulty from another perspective (Blankenship et al., 2011).

During the literature review different methods for reporting efficiency for solar fuels have been identified. This thesis aims towards the full solar fuel process, consisting of five separate processes, each with a unique efficiency. To provide an overview of the total efficiency of converting solar energy into fuels, a reasonable method would therefore be a multiplication of all these efficiencies. This approach is generally synonymous to terminology like solar-to-liquid (STL), solar-to-fuel (STF) or comparable definitions dependent on the desired end product. The most detailed example of this preferred method was reported as 7.7% total conversion efficiency (including losses for electrolysis and CO2 capturing) by Haije & Geerlings in 2011.

However, in scientific literature, STF often refers to the production of hydrogen as final solar fuel instead of hydrocarbons, which results in significantly higher efficiency values as the final steps of the cycle are emitted in the calculation. To avoid confusion, reported efficiencies for solar hydrogen options will be defined here as solar-to-hydrogen (STH), thus calculated as the product of PV and electrolyser efficiencies (Gibson & Kelly, 2008). Most STH are in the order of 10%, for instance the STH for AE reported by Herron et al. (2015). However, significantly higher STH have been demonstrated up to 30% STH in a PV-electrolysis based system (Jia et al., 2016; Montoya et al., 2016).

Finally, calculating fuel efficiency starting from solar irradation or from solar electricity (i.e. equating to approximately 15-25% of the solar irradation) can thus influence the efficiency number by approximately a factor 5. From an energetic perspective, LSF reach efficiencies up to 40% (Kraan et al., 2019) or even 60% (Trieb et al., 2018), yet this cannot be compared fairly to STL pathways, as the output energy is taken as input. When analysed correctly, the 7.7% STL by Haije % Geerlings would equal the 38% reported by Kraan et al., when typically using an average PV efficiency in these systems of 20% (Lips et al., 2018).

For solar fuels, Heeger (2012) suggests a 10% solar-to-fuel efficiency as a main future target, which is already significantly higher than natural photosynthesis (typically < 1%) of which the technology is partly based on attempts to replicate effectively (Blankenship et al., 2011; Roy et al., 2010). Stechel & Miller (2013) strengthen this claim by recommending R&D efforts should only be continued once this threshold of 10% conversion efficiency has been realised. Looking at reported full pathway efficiencies, solar fuels typically do not yet reach this limit, which could be one of the factors that development efforts are not maximised yet.

However, the recently demonstrated PV-electrolysis systems with higher STH provide opportunities for significant efficiency improvements, possibly surpassing 10% STL in the short-term future if additional problems and energy losses of extending this system from STH to full STF are limited. A further observation is how the PV-electrolysis system performs more efficiently than a number of alternative solar fuel pathways, e.g. thermochemical reduction, only reaching 0.8% STF in practice (Haije & Geerlings, 2011; Tuller, 2017) and possible uses of microbacteria (< 5% STF, Lips et al., 2018).

Costs

Most scholars agree that costs are almost single-handedly the main limiting factor of solar fuels, especially because certain technologies within the process are already increasingly available. In table 2, scientific publications containing solar fuel cost indications are summarized. Similar to efficiency, however, ensuring comparable measures to indicate costs are equally important. Most notably, showing results in monetary values per unit of volume (e.g. litres or barrel) differs from a more energetic approach (costs per GJ or kWh) or per unit of mass (cost per kg). All these options have been found in various publications.

The question of how far commercialization of solar fuels has reached is one of the most fundamental ones in this research topic and difficult to answer directly. This manifests itself in extremely diverse data in an extensive literature review by Brynolf et al. (2019), who reported total cost indications of 130 $ - 770 $/MWh for FT-liquids in a 2015 scenario. This would equate to **36 - 214 $/GJ**.

Table 2: reported cost indications from previous literature

Costs	**Fuel**	**Source (year)**
57 $/GJ	General LSF	Trieb et al. (2018)
153 $/GJ (Future target: **36 US dollars/GJ**)	General LSF	Kraan et al. (2019)
92.29 $/GJ	Renewable diesel	Detz et al. (2018)
19.5 – 91.65 $/GJ	Renewable kerosene	Terwel & Kerkhoven (2018)

Final indications in table 2 are levelized to US dollars/GJ for comparison. For converting costs indications per L or kg, the results provided by Trieb et al. (2018) were used, which is one of the few papers providing a full range of different cost units. For converting bbl into GJ, figure 2 was used again, which assumes 5.5 GJ for barrel of solar fuels. However, it should be noted that these papers may use deviations in assumptions, end fuel (e.g. specifically focused on kerosene).

In addition to total cost indications for the entire pathway, Kraan et al. (2019) provide a metric of how the cost are divided between the 5 processes: DAC, PV electricity and electrolysis combined contribute to roughly 85% of the total costs in this model, whereas CO2 activation and FT have relatively lower costs.

Based on recent trends, both DAC and PV electricity generation have positive prospects. Due to the rapid costs reduction of PV electricity, further reductions are expected, as the electricity price is steadily decreasing (Inganäs & Sundstrom, 2016; Detz et al., 2018). Furthermore, DAC is characterised by impressive cost reductions, from 600 $/tonne of CO2 in 2011 to recent pathways possibly achieving costs 6 times lower, which is the largest cost reduction of these processes and rapidly lowers the position of DAC as the highest cost contributor of the pathway in today's model (Kraan et al., 2019). For electrolysers, costs are typically still high (Detz et al., 2018).

Finally, for comparison with current fossil-based alternatives, Detz et al. (2018) calculated costs for pathways of both pathways using methods for LSF comparable to the aimed pathway of this paper. While the literature shows how quantifying costs can still lead to dispersing data, the only observation that can be concluded without question is how all renewable pathways are still more expensive than fossil pathways, whether for hydrogen production via AE (factor 4 higher) or renewable diesel via RE and FT (factor 3 higher) (Detz et al., 2018).

Solar fuel TRL

Table 3 contains examples of TRL scale usage within the solar fuel scientific research field.

Table 3: Previous solar fuels and TRLs

Solar fuel TRL	Source	Scale	Comments
Hydrocarbon synthesis, electrolysis, PV: 5 DAC, CO2-activation: 2-3	Purchase et al. (2019) Figure 6	Five-point scale	Only ordinal scale, no TRL numbers
Varying 1-5 (not possible to use a single score)	Lewerenz & Sharp (2018) Figure 7	Five-point scale	TRL scale only for solar fuel research hubs
3 (Solar fuel) 7 (Upscaling solar fuel)	TU Delft (n.d.-a) TU Delft (n.d.-b)	Basic numerical TRL scale (1-9)	No further explanation or date; research projects likely ongoing
Hydrocarbon via FT: commercial in 2019-2024 Syngas production: commercial 2016-2018	Passalacqua, Centi, & Perathoner (2015) Figure 8	Time scale	Technology roadmap; prediction of commercialization

Out of the sources listed above, only the assessment by TU Delft has given specific TRL ratings on the commonly known 9-level TRL scale, which makes it the most compatible to the current study. Here, a notable difference in TRL is distinguished between solar fuels in general and specifically upscaling solar fuels (TRL 3 and TRL 7, respectively). Unfortunately, further explanations and methods resulting in these metrics are hardly available, possibly because there is still ongoing research.

Purchase et al. (2019) have not only provided TRLs for the entire solar fuel research field, including TRLs for biological routes and the artificial leaf, but also highlight ordinal differences within the subprocesses of PV-electrolysis solar fuel production to be analysed here.

Finally, the figures by Lewerenz & Sharp (2018) and Passalacqua et al. (2015) prove how both solar fuel research projects and different solar fuel uses can differ significantly in terms of perceived readiness. Beside the perceived TRLs, differences between the expected commercialization periods of the relevant components are striking as well.

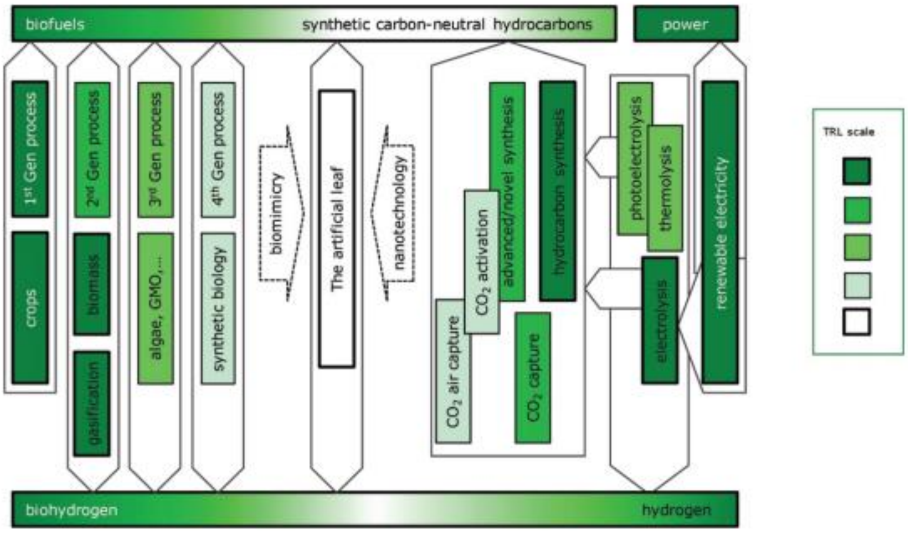


Figure 6. TRL scale indications of solar fuels (Purchase et al., 2019)

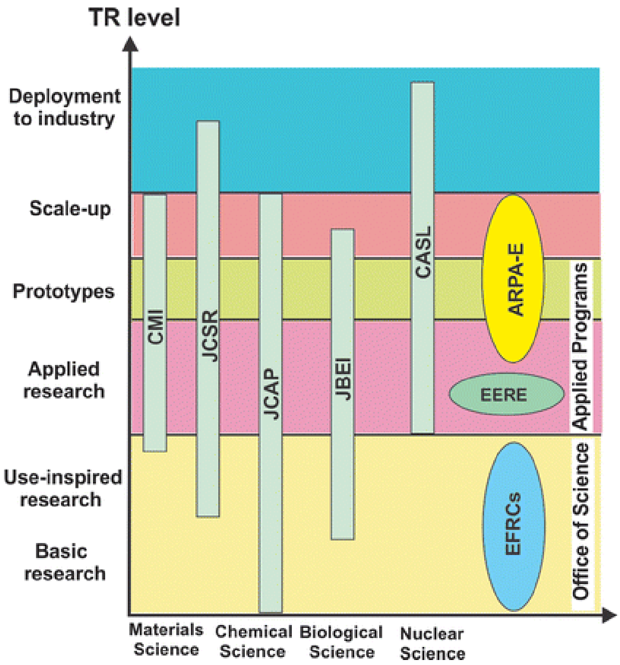


Figure 7. Technology readiness indications of notable research projects (Lewerenz & Sharp, 2018)

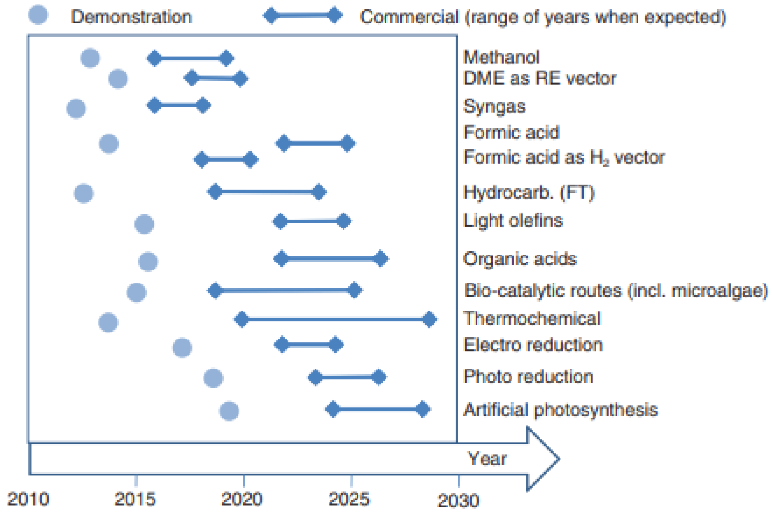


Figure 8. Technology roadmap of different solar fuel production components (Passalacqua et al., 2015)

Solar fuel TRA

Assigning only one TRL rating for the entire production process can be problematic as the individual processes are likely to differ significantly in terms of development and commercialization, as illustrated by some of the TRL scales used earlier. Although all processes are initially analysed individually, since all processes are included in the final product of a solar fuel, the practical TRL of the general solar fuel application will be determined by the least matured technology, i.e. the lowest TRL score. Purchase et al. (2019) already suggested that capturing and activation of CO2 will likely cause the most problems as there are assigned the lowest TRL. Moreover, Haije & Geerlings state that “with the exception of RWGS, the processes are (sub-)commercially available already” (2012, p. 8609), suggesting that placing CO2 activation lowest on the TRL scale would be valid.

Usage of suitable catalysts for RWGS are crucial, yet, as Inganäs & Sundström (2016) argue, the right catalysts do not exist at the moment. Likewise, DAC is still considered in its infancy and it is expected to blow up on a large scale only from 2065 onwards (Chen & Tavoni, 2013). Because of this, these processes will be analysed via TRA first, as there are expected to predominantly determine the final TRL of solar fuels.

From purely a TRA perspective, results for technologies which are already system-integrated are less useful than upcoming technologies in the midst of climbing the TRL ladder. In this production cycle, both electricity production via PV and hydrocarbon production via FT are in a more mature state and already commercially in use. Electrolysis is also widely established, not only used commercially but also in large-scale productions worldwide. These components should therefore theoretically already be at least close to TRL 9, making the intended TRA less useful. For AE, PV and FT, starting TRLs will in principle be considered 9 for this paper. Nonetheless, the three remaining processes will be assessed briefly.

1. Direct air capture

Figure 3 already reported 4 common techniques for DAC. In previous TRA on DAC by Viebahn, Scholz & Zelt (2019), absorption and adsorption were identified as most relevant processes and were distinguished based on thermal energy demand, which resulted in reported TRLs for three main categories of DAC. While this paper does not focus specifically on differences between DAC techniques, it should be noted that TRA results can be influenced by this approach, as Viebahn et al. have showed.

TRL 1-3

The potential new capabilities of DAC have been discussed thoroughly in the context of CO2 mitigation. Many papers consider DAC a promising alternative to reduce CO2 emissions and sometimes even a necessary method with the eye on the agreement of limiting global warming (Beuttler et al., 2019).

Compared to other carbon capture possibilities, DAC enables more flexibility within the energy infrastructure, as DAC does not require to be linked to an emission source directly (Chen & Tavoni, 2013). Therefore, applications of DAC appear to have very attractive potential which can be used in a variety of situations.

In terms of risks and requirements, DAC is typically considered a high economic risk (Chen & Tavoni, 2013). Viebahn et al. (2019) agree on this, estimating technical risks rather low but economic risks high. Further R&D should be possible to improve the techniques. Numerical models can calculate the amount of carbon to be captured and its energetic properties, for instance the calculated requirement of roughly 5 GJ of electricity for DAC to synthesise one barrel of solar fuel (Kraan et al., 2019).

Once again, basic technologies of air capturing were already made in the last century (Ranjan & Herzog, 2011), which have possibly led to clear identification of the technology. Pathways with usage of direct air capture in larger systems have also been identified. In fact, possible implementation of DAC in the solar fuel production process, visualized in figure 2, is a prime example of this. However, details about the characteristics still leave room for further specification, e.g. in the range of cost indications, which is still varying significantly in the literature.

Pathways of DAC in larger systems have been developed but are aimed towards very long term solutions. The problem is that the ambitious environmental targets of CO2 mitigation more or less require DAC to be developed further in a short time span in order to achieve this (Ranjan & Hertog, 2011), which may not be realistic at all. Nonetheless, the first analytical model of DAC usage has been created by Keith et al. in 2018, providing an important step towards TRL 3.

TLR 4-6

While it can now be concluded that DAC technologies have been identified accordingly and are undoubtedly researched to clarify and improve its components, we now focus on development of the technique. TRL 4 and 5 require the technology to be tested both in laboratory and application-relevant environments. Climeworks in Switzerland already developed laboratory prototypes in 2009, followed by more relevant applications in 2011 (Beuttler et al., 2019). For two out of three DAC categories analysed by Viebahn et al. (2019), demonstrational applications are already identified and utilized, providing clear examples of demonstration phases.

TRL 7-9

Continuing the development of their DAC project, in 2017 Climeworks opened the first operational DAC plant in Switzerland. More operational plants steadily followed it, meaning the TRL has already reached level 9 following the ESA guidelines. While Climeworks itself ambitiously ranks the technique at TRL 9 (Beuttler et al., 2019), this specific plant by Climeworks is the only DAC category (defined as DAC for low temperature, as opposed to no temperature and high temperature DAC) to do so. Furthermore, Beuttler et al. report no observations of DAC technology within TRLs 7 – 8, so it is feasible that the general TRL of DAC cannot already be considered 9 despite current operating installations. Finally, combining comparable DAC plants to an operating solar fuel system with all 5 components will likely result in additional challenges and costs. Therefore, this can provide a valuable claim to already consider DAC at TRL 9. However, since this paper is mainly considering this in the context of a full solar fuel system, it is more sceptical to consider DAC also at TRL 9 as a component of the entire system. Moreover, the current operating factories are mostly independently working and are not specifically combined with RE initiatives or further CO2-reduction.

This would mean that the technology has currently achieved TRL 7, at the stage where the system is clearly modelled and DAC is already fully demonstrated and even working in relevant applications. Beuttler et al. (2019) report how Climeworks is planning on more DAC plants and has demonstrated combination into liquid solar fuels, which would lead the way towards collectively achieving TRL 9 for solar fuels as well.

Still, the technology is at the crucial stage of transforming this into a fully working system (i.e. specifically for solar fuel production) that will not bring too many additional costs in order to reach TRL 8 and eventually push DAC to TRL 9. Since examples of TRL 9 are already fully available, although mostly independent exceptions in comparison with other DAC techniques, the goal of reaching TRL 9 in a suitable time period, for example 2050, provides many opportunities for intensive developments in the coming years.

2. CO2-activation

In addition to the claim by Ingenäs and Sundstrom (2016) that catalysts do not yet show suitable characteristics, Herron et al. (2015) state that – compared to water-splitting – the technology and catalysts for CO2 reduction have been not been studied and remain much less efficient, particularly demonstrating low conversion rates and selectivity. Once again, we only focus on the electrochemical reduction route of CO2, i.e. powered by electrolysis from PV electricity.

TRL 1-3

The possible advantages of CO2-activation are clear: after reducing CO2 from the ambient air, converting this directly into feedstocks for liquid fuels will not emit additional carbon. Unfortunately, plans about drastically increasing the performance for systems with CO2-activation components are mostly theoretically oriented still, as the main research focus is still on material research for suitable catalysts. For instance, summaries of results for different catalysts can be found in Herron et al. (2015) or Roy et al. (2010).

While it now becomes clearer which catalysts are more beneficial, further chemistry challenges make it harder to further develop this into suitable environments. However, it can be concluded that basic principles and possible appliances have been identified clearly and R&D has started, resulting in the definition of TRL 3 being reached.

TRL 4-6

The catalysts research has brought usable conclusions so far, e.g. various calculation of possible conversion efficiencies (Herron et al., 2015). Based on this research, laboratory environment experiences are still crucial for further development, placing the current maturity between the phase of transforming the current characteristics found in the lab into placing this in further relevant environments. A body of scientific literature have provided the lab-scale properties into a possible environment. However, it would not be feasible to provide efficient CO2-reduction technologies within a full solar fuel PV-electrolysis system, which would be the most relevant environment here. As Schmidt et al. (2018) conclude, CO2 activation via RWGS is established on small scale only and requires significant scale-up. Therefore, Co2-activation via electrochemical reduction would achieve TRL 5 out of 9.

3. Alkaline electrolysis

The main developed options for electrolysis are alkaline electrolysis (AE) and polymer electrolyte membrane (PEM) electrolysis. Out of these options, AE is the most commercial developed technology for electrolysis (Tuller, 2017), currently producing roughly 4% of mondial hydrogen production (Hinkley et al., 2016). By already covering a significant part of mondial production, conventional AE is from a TRA perspective thus surpassing PEM, which has reached TRL 7 (Wulf, Linssen, & Zapp, 2018). Looking at the current state of AE, it is viable to assume the established AE technology as baseline for solar fuel production to minimize costs and increase overall performance.

4. PV electricity generation

PV installations for consumers are being provided commercially. As the projected installed mondial PV capacity and its cost indications already showed, PV is generally approaching the limit of conventional electricity. Current electricity costs are 0.5 €/Wp, close to the target price of 0.4€/Wp for competition (Inganäs & Sundström, 2016). Although many techniques and appliances with PV panels have been developed and many of them are still in R&D, systems with general (i.e. silicon) PV panels, most notably on rooftops, can be realised easily and are more often a common sight in urban areas. It is needless to say that in that case TRL 9 has been reached, as the capacity commercialised silicon PV is not only increasing steadily, its costs keep decreasing as well. Potential alternatives for the standard PV panel and more possible complicated appliances with the standard PV panel are on the rise, paired with specific development requirements and lower TRLs (Inganäs & Sundstrom, 2016; Folkerts et al., 2017). However, for solar fuels, PV is used to primarily provide electricity and does not require many advanced characteristics to succeed for this cycle. Therefore, it is reasonable to assume that basic PV technologies are used for this thesis.

5. Fischer-Tropsch synthesis

FT processes can also be considered TRL 9, looking at the current applications for conventional fuel production. As figure 1 shows, FT is used for synthesis for nearly all fuels, including conventional fossil fuel based pathways. This results in FT already in fully industrial use today, additionally having relatively low cost contribution for a barrel of solar fuel (Kraan et al., 2019).

It should be noted that current FT processes use coal or natural gas based syngas as feedstock and no renewable pathways (Salvi et al., 2013). Furthermore, assigning a single TRL to the entire spectrum of FT is problematic, as shown by Jarvis & Samsatli (2018), who argue that previous processes can influence its maturity, resulted in a final TRL range of 5-9 for FT.

In this report, we do not consider syngas production a part of FT technology, which would not change the maturity of FT; it simply shows how renewable syngas production still needs further developments, as already concluded above.

Final TRA

In summary, the final position of the TRLs on the TRL scale are visualized in the table below.

Table 4: Final TRA results

Component	TRL	Assessment summary
PV	9	Likely to continue decrease costs together with full commercial technology
FT	9	Relatively low cost and widely used for fuel production
AE	9	The choice for AE pushes TRL to 9
DAC	7	Full DAC plants currently in operation, but brings the challenge of integration into solar fuel cycle
CO2-activation	5	Stagnated on research for effective catalysts and/or further materials

Limitations and further research

The scope of the analysis on solar fuels in this paper has largely disregarded two important factors within its research theme: (1) the role of solar hydrogen as very likely the first relevant solar fuel to be fully implemented and (2) the variety of applications within the solar fuel field, by focusing on the PV-electrolysis pathway. Although valid reasons for these restrictions are provided, when plotting future developments of this technique, both these alternatives should not be ignored. In fact, hydrogen will play a key role in transitioning the energy system, but as the last part of this paper is directly focused on aviation where this would be unlikely, hydrocarbons fuels were a preferred option in this scenario. The PV-electrolysis was preferred based on the current advantages of development state in comparison to alternative solar fuels pathway. However, it should be noted that a solar fuel technique which is in its infancy now could replace alternative solar fuel routes rapidly and be implemented quickly in a future scenario.

Of the components who were estimated at TRL 9 (i.e. PV, AE and FT), the author acknowledges that the result for the electrolysis process in particular may lead to further discussion. AE was chosen as the most established electrolyser choice, yet the potential for PEM and even SOE (a relatively new technology rapidly developing) in combination with PV was indicated in many cases. For instance, Centi & Perathoner (2010) already showed how maximized efficiency was achieved with PEM electrolysers and Detz et al. (2018) included cost projections for both electrolysers, showing how PEM costs are estimated to decrease significantly faster than AE costs, even though PEM is currently more expensive. Therefore, exploration of solar fuels in combination with these different electrolyser types may be suitable for further research, considering the crucial role of hydrogen in the cycle.

Possible pathways for solar fuels: transportation and aviation

To provide a better look for possible scale-up and resulting implementation of LSF in the energy system, usage of these fuels in the transportation sector is explored further.

In European context, the European Expert Group (EEG) confedered in 2018 about the use of renewable fuels in transportation and aims towards biofuel as third main fuel option after electricity and hydrogen (Barrett, 2011). Synthetic fuels – which includes solar fuels – are briefly suggested as alternative, but for these synthetic fuels, only biomass, coal and gas-to-liquid pathways are discussed in detail. Therefore, it seems that in current policies, other sustainable alternatives are prioritized for the transport sector.

Aviation is typically seen as the prime example of using alternative liquid fuels because of the practical difficulties of electrification or transitioning towards hydrogen within this niche, distinguishing this sector from other examples in the transportation sector where this is indeed possible (Detz et al., 2018; Terwel & Kerkhoven, 2018). This makes the aviation an 'exception' for transportation, as usage of kerosene cannot be easily replaced in a similar way like in other transportation modes, e.g. the current growth of personal cars with electric batteries and the development of hydrogen-based personal cars. Simultaneously, aviation is still rapidly growing, resulting in increasing energy consumption and carbon dioxide emissions (Kousoulidou & Lonza, 2016). To this end, scientific interest for carbon neutral aviation has increased and various reports have thoroughly examined the possibilities of carbon neutral aviation, as solar fuel for aviation might sooner be a reality in comparison with sectors where hydrogen and/or electricity can provide a significant part of the energy system renovation.

This does not mean that use of electricity and/or hydrogen options for aviation cannot be a reality. The Kalavasta report mentions electric aviation, however, the maximum range is very low, which means they are not a viable option for the distances to be covered in (commercial) aviation, nor is it likely to happen in the coming decades. Therefore, STL is seen by Kuhn, Falter and Sizmann (2011) as the only sustainable kerosene production pathway which is also both suitable and scalable before 2050. This leaves two main green kerosene options: synthetic kerosene and bio-based kerosene. Both the Netherlands (SER, 2014) and Europe (Barrett, 2011) rely on mainly developing biofuels for aviation, the SER even concluding that biofuels are "the most realistic option for aviation"(2014, p. 27). While the SER report does mention the opportunity of sustainably synthesize energy carriers such as hydrogen from solar energy and CO2 in other transportation sectors, for aviation this is not the case. The EEG agrees on this and only suggests biomass-derived kerosene as viable option as well.

However, while bio-based kerosene shares a few advantages with solar-based fuels, it generally lacks a suitable degree of scalability compared to STL options (Kuhn et al., 2011; Trieb et al., 2018). For instance, from an environmental perspective, biofuels require around 3000 times more water compared to solar fuels (Terwel & Kerkhoven, 2018). Furthermore, the required infrastructural developments for solar fuelled kerosene are already largely available. For instance, the use of the large industrial and transportation assets in West-Netherlands can provide crucial developments in terms of infrastructure which would enable CO2-neutral fuel production (Terwel en Kerkhoven, 2018).

Finally, full solar pathways towards jet fuel are not yet developed, but research, small-scale or lab-scale development and pilot projects are ongoing today (Schmidt et al., 2018). In 2014, the first lab-scale solar fuel was synthesised (i.e. TRL 4 and above), thus also forwarding the TRL of this specific application (Kousoulidou & Lonza, 2016). Furthermore, Terwel & Kerkhoven argue that with a non-extreme set of assumptions (e.g. a growing oil price and usage of CO2 taxes in the future), carbon-neutral kerosene could already become an option in 2030.

Conclusion

In this paper, the current and potential state of liquid solar fuels via PV-electrolysis has been analysed via TRA of five major components within the production stage: PV, DAC, CO2 activation, AE and FT. Additionally, key challenges and transport sector options have been explored via available data and literature.

Recent developments and strategies for limiting carbon emissions have led to further interest in synthetic fuels to replace the current fossil-based fuel production. Liquid fuels from solar energy can overcome typical RE challenges of intermittency and energy storage and can push the boundaries of RE beyond electricity generation only. The need of storing clean energy into the for most sectors absolutely necessary liquid fuels is high, paving the way for a future of liquid solar fuels.

Out of the various techniques for solar fuels, PV-electrolysis has been focused on as main pathway in this report, as this pathway offers an infrastructural advantages over alternatives. Initially, literature review suggested efficiency improvements and cost reduction, after which both efficiency and cost studies were analysed. Typical efficiencies showcase <10% STF, which is significantly higher than alternative pathways, yet further development towards the target of 10% are encouraged. Recent developments could lead to surpassing this target, but still need to overcome the step from hydrogen production towards fuels. Specific cost indications for STL vary, but are all undeniably significantly higher than fossil-based pathways. Therefore, cost reductions should be decreasing steadily in order for achieving serious competition in the coming decades.

To assess the technological maturity of PV-electrolysis solar fuels, TRA was conducted according to ESA guidelines. Initial literature review suggested both DAC and CO2 activation to be the limiting factors to determine the final TRL by showcasing the least developed readiness levels. To the author's knowledge, no CO2-activation process via RWGS has been reported significantly beyond laboratory and demonstration scale, corresponding to a TRL of 5. Further R&D, particularly for catalysts improvements, should be made first. DAC achieved TRL 7 as larger scale applications could be a reality for the solar fuel pathway. Moreover, DAC has made significant steps towards large-scale utilization recently with the first commercial DAC plants currently operating. PV, FT and AE were all reported to be currently available in commercialised appliances, corresponding to TRL 9, yet need to evenly contribute to major cost reductions of LSF as well.

Since aviation is a specific example of fossil fuel dependency for the transportation sector, where solar fuels could become viable with lack of suitable alternative for fossil fuels, an analysis in this sector was conducted as final stage of the thesis. Current policies seem to tend towards sustainable biofuels for sustainable aviation fuels in the future. However, based on the conducted literature review, TRA and aviation scenarios, this paper suggest further consideration for LSF in aviation and efforts for intensive LSF development. While bio-based kerosene may be more attractive economically, it brings additional challenges, such as resulting net carbon emissions, scalability and further environmental problems compared with solar-based synthetic kerosene. Henceforth, from a sustainable perspective, I argue that kerosene produced via PV-electrolysis should receive more attention in the context of reducing CO2 in the aviation sector.

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Appendix I

TRA checking questions for all 9 levels (courtesy of ESA, 2009)

TRL 1

- TRA QUESTION 1.1: Has a hitherto-unknown scientific fact or principle been discovered that suggests one or more potentially useful new capabilities? What is the new fact or principle? What are the new capabilities?
- TRA QUESTION 1.2: For a desired new capability, is (are) there (a) fundamental, perhaps newly discovered scientific fact and/or principle that suggests a path to technical feasibility to implement the new capability on the basis of the principles described in 1.1? What is the new capability? How can it be technically implemented?
- TRA QUESTION 1.3: Have conceptual studies suggested any possible new concepts and/or technology that might emerge as a result of the new phenomena observed?
- TRA QUESTION 1.4: For the scientific phenomena involved, is further scientific research possible in the foreseeable future? Does it appear likely that technology R&D will be viable? Can the technical risk and required effort be evaluated?

TRL 2

- TRA QUESTION 2.1: Has a potential new technology been identified that employs the new scientific fact or principle identified at TRL 1 to be applied in a component or system in such a way so as to establish a potentially useful new capability? What is this new conceptual approach? On what scientific fact or principle is it based?
- TRA QUESTION 2.2: Has the potential new concept and/or technology been framed with sufficient detail that possible future functional and/or environmental application requirements have been defined?
- TRA QUESTION 2.3: Has an analytical study been performed that confirms the potential usefulness of the new concept and/or technology identified above in Question 2.1 for the application described in Question 2.2?
- TRA QUESTION 2.4: Is there a viable path forward that would lead from the invention to the system application? What are the requirements of this path to realize the new capabilities? Can the technical risk and required effort be evaluated?

TRL 3

- TRA QUESTION 3.1: Have the key technologies and their functions been clearly identified and defined that would enable the utilization in the context of one or more system applications?
- TRA QUESTION 3.2: Has a prospective family of applications been identified, even if superficially, in terms of a possible family of operational environments, performance requirements, and relevant technologies?
- TRA QUESTION 3.3: Have the critical functions of the new technology described in Question 3.1 been validated analytically and/or experimentally so as to establish the technology to be used to implement the application(s) described in Question 3.2?
    - If analytical studies have been used to demonstrate a new capability, has this new conceptual approach been clearly modeled? Do the results of completed analytical studies verify that the prospective applications of the technology are valid and would, if developed successfully, result in the effective implementation of the new capability?
    - If laboratory experimentation has been involved or used to demonstrate a new concept, has this experimentation been conducted under rigorous, verifiable conditions? Do the results of completed experiments verify that the prospective applications of the technology are valid and would, if developed successfully, result in the effective implementation of the new capability?
- TRA QUESTION 3.4: Is there a viable path forward that would lead the experiment and/or analytical result forward to a future application? What are the likely capabilities that will be needed to follow that

path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

TRL 4

- TRA QUESTION 4.1: Has the new technology and/or concept been clearly described? What are the critical functions that would be performed by any intended applications of the conceptual approach, device, and/or software? What are the new capabilities that would result from this new concept?
- TRA QUESTION 4.2: Has a prospective application been identified and defined in sufficient detail in terms of expected operational environment, performance requirements, and constituent technologies? Are the interactions among those elements well understood?
- TRA QUESTION 4.3: Has the new concept, technology and/or approach been clearly and rigorously modeled and tested? Is it technically feasible? Do the results of analytical and/or laboratory studies verify that the new technology can satisfy the requirements of the prospective applications (per Question 4.2 above)? What metrics were used to conclude that the laboratory experiments(s) worked as desired?
- TRA QUESTION 4.4: Based on the results, is there a viable path forward that would lead the experiment and/or demonstrations forward to the envisioned future application? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

TRL 5

- TRA QUESTION 5.1: Has the new concept, technology and/or approach been clearly described and modeled? What are the critical functions that would be performed by the conceptual approach, device, and/or software? What are the new capabilities that would result from this new concept?
- TRA QUESTION 5.2: Has a prospective application been defined with sufficient fidelity that the necessary technological elements involved in the new capability have been fully identified? Are the interactions among those elements well understood? Have the functional, operational environment and performance metrics for this application been defined, and do prospective customers agree?
- TRA QUESTION 5.3: Have laboratory demonstrations been performed rigorously and successfully that included key elements being tested individually and/or in an integrated fashion? In such tests, were the results consistent with the characteristics (identified in Question 5.2) that the new technology must possess in order for a prospective future application to be technically and/or economically viable? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the laboratory demonstration(s) worked as desired?
- TRA QUESTION 5.4: Is there a clearly identified path forward that would lead the experiment and/or demonstrations forward to the specific application described in Question 5.2? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

TRL 6

- TRA QUESTION 6.1: Has the new system (or subsystem) that incorporates the new technology been clearly described and modeled? What are the critical functions that would be performed by the new technology in the system? What are the new capabilities that would result?
- TRA QUESTION 6.2: Have one or more specific applications been defined with sufficient fidelity that the detailed technologies involved in that sub-system or system can be identified, including preliminary designs and cost estimates? Have the relevant technology requirements been identified and are the interactions among the various technologies within the system well understood?
- TRA QUESTION 6.3: Have rigorous system-level demonstrations been performed successfully in a relevant environment? Have those demonstrations included key elements being tested individually and/or in an integrated fashion? In such tests, were the results consistent with the levels of performance, cost, etc. that the new technology must possess for the intended system applications to be technically

and/or economically viable? What functionality was demonstrated? Was the demonstration been clearly documented and articulated? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the system-level demonstration(s) worked as desired?

- TRA QUESTION 6.4: Is there a viable path forward that would lead the demonstration accomplished forward the intended application? Is a demonstration at TRL 7 needed, and if so, why? What are the likely capabilities that will be needed to follow that path (including operational environments, testing environments, etc.)? Can the technical risk and effort be evaluated?

TRL 7

- TRA QUESTION 7.1: Has the new system that incorporates the new technology been clearly described and modeled? What are the critical functions that would be performed by the new system / technology? What are the new capabilities that would result?
- TRA QUESTION 7.2: Has the specific intended application been fully defined including all functional and environment requirements.
- TRA QUESTION 7.3: Have rigorous and verifiable system-level demonstrations been performed successfully in the actual expected operational environment (e.g., in space for spacecraft)? Have those demonstrations included key elements being tested in an integrated fashion? In such tests, were the results consistent with the levels of performance, cost, etc. that the new system must possess to fully satisfy the requirements identified in Question 7.2? What functionality was demonstrated? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). What metrics were used to conclude that the system-level demonstration(s) worked as desired?
- TRA QUESTION 7.4: Is there a viable path forward that would lead from the system demonstration accomplished forward to the intended application? What are the likely capabilities that will be needed to follow that path forward? Can the technical risk and effort be evaluated?

TRL 8

- TRA QUESTION 8.1: Has a production unit (i.e., the actual subsystem or system deliverable from the project) been fully described and successfully manufactured?
- TRA QUESTION 8.2: Has the specific system in which the technology is to be used been defined with sufficient fidelity to allow accurate cost estimates? Have detailed designs for the system been identified both in terms of performance and operational environment? Are the interactions among the various technologies within the system well understood?
- TRA QUESTION 8.3: Has system-level testing verified that the new technology(ies) performed successfully in the appropriate test environments? Are the tests performed representative of the whole environment, in term of type (temperature, mechanical stress, radiation, duration…), sequence (vibration first then thermal…), simultaneity (radiation with temperature…). Has the testing included key elements being tested individually and/or in an integrated fashion? To what extent did the selected new technologies involved play a significant role in the failure or the success of the project? Has a production unit been qualified to the satisfaction of one or more customers?
- TRA QUESTION 8.4: Is there a viable path forward? Are there any remaining barriers to system/mission operations as originally planned? If there are such barriers, are they amenable to solution through changes in mission operations plans? Can the technical risk and effort be evaluated?

TRL 9

- TRA QUESTION 9.1: Is the new technology fully described in terms of its final manufacturing and operational plans. (sic)
- TRA QUESTION 9.2: Is the new unit (subsystem or system) being produced at the levels of performance, cost, quality, reliability, etc. that were originally anticipated? Are any previously

unforeseen barriers to cost effective manufacturing of high-quality units that operate as intended been eliminated?

- TRA QUESTION 9.3: Has the new technology performed as expected? Are the subsystem and the various technologies within the system operating as expected?
- TRA QUESTION 9.4: Are significant barriers remaining to successful system operations (if any) been removed, possibly through applications of new technology? Is the customer happy? Can performance improvements be achieved (if required) with further technology developments? Can the technology be reproduced given the current know-how? Can the technical risk and effort be evaluated?