System-Level Simulation of a Solar-Driven Liquid Fuel Production Plant via Gasification-Fischer–Tropsch Route

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Abstract. Conversion of algae into liquid fuels via solar-driven supercritical water gasification (SCWG) with steam methane reforming (SMR) and Fischer–Tropsch (FT) synthesis offers a promising approach for production of clean fuels. While much research has been dedicated to the analysis of biomass gasification, methane reforming and FT synthesis separately, little emphasis has been placed on a fully integrated system based on these components especially when a variable heat source – i.e. concentrating solar thermal (CST) – is involved. As such, this paper investigates the annual dynamic performance and techno-economic feasibility of this technology at a system level. A detailed steady-state model of the SCWG-SMR and FT plants is developed in ASPEN Plus software. Based on performance curves of key component quantities at design and off-design points, an energy-based, system-level model of the whole solar fuel plant is developed in OpenModelica. The solar field is sized such that it can deliver 50 MW_{th} to the receiver at design. The results of the parametric study suggest that the optimal solar multiple and syngas storage size are 3.5 and 16 hours, respectively, leading to a levelised cost of fuel (LCOF) of 3.2 AUD/L (~2.3 USD/L) and a capacity factor of ~71%. The total capital and annual operational costs of the system are found to be ~162 M-AUD and ~24 M-AUD per year, respectively. Although the estimated LCOF in this study seems to be relatively high compared to fossil fuel-based petroleum products, this technology is expected to be economically competitive in the near future through e.g. upscaling the plant size and further reduction in the algae production cost.

INTRODUCTION

Concentrated solar power (CSP) technologies are currently under rapid development and deployment due to their potential to reduce the use of fossil fuel resources and to alleviate greenhouse gas emissions. The high-temperature thermal energy collected by CSP can be utilised for a wide range of applications such as power generation, industrial processes, and biochemical/thermo-chemical reactions. With growing demand for liquid fuels and the diminishing fossil fuel resources, developing a clean approach for the production of liquid fuels has become increasingly attractive in recent years. One clean way is to convert microalgae biomass into liquid fuels through supercritical water gasification (SCWG), steam methane reforming (SMR) and Fischer-Tropsch (FT) synthesis. Traditionally powered by conventional fossil fuel resources, gasification systems can be retrofitted such that they use concentrated solar thermal energy as the driving heat source. The syngas produced from the solar-driven gasifier can be converted to high value transportation liquid fuels via the FT synthesis. Since much of each technology has already been proven at commercial scales, production of solar fuels via the SCWG-SMR-FT route can therefore be a promising and sustainable alternative to conventional petroleum-based fuels [1, 2, 3].

Unfortunately, there has been no convincing commercial business for solar fuel systems to date, mainly due to an acute lack of design and operational knowledge of this technology in the presence of fluctuating solar resource. In fact, system complexity and the lack of a standardised design guidelines and system-level performance optimisation methods have limited these systems to research and testing stages [1]. To make matters worse, while there have been only a few studies on the simulation and experimental analysis of solar gasification systems [3, 4, 5, 6], to the best of the authors' knowledge, there has been no research and development on the techno-economic annual performance of a solar gasification plant integrated with an FT unit at a system level. Thus, a systematic research is required to bridge this gap and find solutions to make solar-powered liquid fuel technology efficient, reliable and cost-competitive.

Motivated by their significant potential, this paper aims to evaluate the techno-economic feasibility of solar-driven fuel production technology based on coupling solar-driven SCWG and SMR reactors with a downstream FT reactor. The model is developed in OpenModelica in order to conduct annual simulations of the plant. A detailed economic model of the plant is also developed as a wrapper to the Modelica model in order to determine the levelised cost of fuel (LCOF). A parametric study of the system is performed in order to evaluate the influence of key design parameters (i.e. solar multiple and syngas storage size) on the plant performance from a techno-economic standpoint.

MODEL DESCRIPTION

The flow diagram of the proposed plant is illustrated in Fig. 1. The main components of the plant are a heliostat field, a dual thermo-chemical receiver (consisting of separate SCWG and SMR reactors [7]), a syngas storage tank, an FT unit (including an FT/hydrocracking reactors, distillation column and Rankine cycle) and a control system. The concentrating solar energy collected from the solar field is used to drive the SCWG and SMR reactors, converting microalgae as feedstock into syngas. Dry microalgae (as the feedstock) is fed into the SCWG reactor at the design temperature of 605 °C, and is converted to methane-rich gaseous products through the (endothermic) SCWG process. The main components of the stream exiting the SCWG reactor are H_2, CH_4 and CO_2 along with a small amount of CO. The resulting gaseous products are then directed into the SMR reactor, thereby producing syngas containing mostly H_2 and CO. It should be noted that depending on the operating conditions of the FT reactor, a fixed H_2:CO ratio is required in order for the FT synthesis to occur [8, 9, 10]. The required ratio can be achieved by either supplying extra H_2 – e.g. from low temperature photovoltaics (PV) – into the algae-derived syngas [7] or dumping carbon in the form of CO_2 from the SCWG reactor. In this study, the latter approach has been considered to match the H_2:CO ratio. The collected solar-driven syngas is then stored in a storage tank and can be used later to drive the FT reactor at the downstream in order to generate liquid biofuels – i.e. petrol and diesel. The heat (at 200 °C) released from the exothermic reactions at the FT reactor is recovered to drive a Rankine cycle to produce electricity, which supplies part of the compressor power consumption at the reactor. The syngas storage plays an important role in the solar fuel plant, in that it acts as a buffer to overcome the intermittent nature of solar energy. It also provides residence time buffering to the FT reactor, thereby preventing it from frequent on/off cyclings.

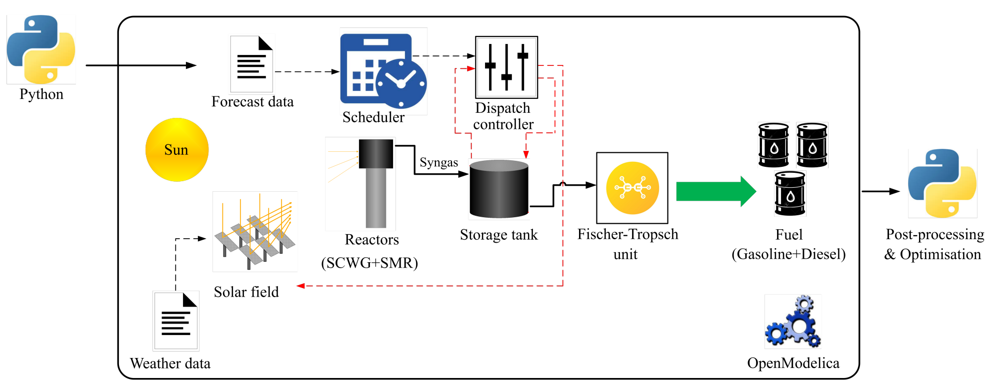

FIGURE 1. Flow diagram of the proposed solar-driven fuel plant for petrol and diesel production.

A detailed steady-state physical model of the plant has been developed in ASPEN Plus. Through (design and off-design) simulations of the physical model, polynomial curves have been obtained to model key component quantities, which are then combined to form an energy-based dynamic model of the plant in OpenModelica – an open-source implementation of the object-oriented Modelica language used for modular modelling and simulation of dynamic systems. The development of the dynamic model is necessary to evaluate the performance of this technology under variable solar-derived thermal source. In order to simulate some technical constraints in a real-world plant, a number of control logics have been implemented in the main components, including operational cut-off points and startup/shutdown times. Little emphasis has been placed on the latter in the current literature [11]. A linear ramping rate has been considered for both the SCWG and FT components. The solar field was sized such that 50 MW_{th} of concentrated solar radiation is delivered to the receiver (i.e. SCWG/SMR reactors) at the design point. The annual optical efficiencies of the heliostat field assumed layout as a function of solar position have been calculated externally by the SolarPILOT optical analysis tool, and provided to the solar field model as a lookup table. A typical meteorological year data set (in TMY3 format [12]) provides the input weather data to a weather component in which a sub-component is defined to calculate the Sun position. The dispatch of syngas to the FT reactor is controlled by a dispatch control component. Once the tank is full, this component sends a signal to the solar field in order to defocus part of the heliostat field. A simple forecast-scheduling scheme based on perfect one-day-ahead prediction of solar irradiance levels has been considered, ensuring a minimised number of shutdowns of the FT reactor during the nighttime, thus avoiding long and costly startups for products stabilisation. While the calculation of the capital and operating costs (including the cost of algae and H_2) of the plant is conducted within the OpenModelica platform (assuming 2016 AUD cost index), the process of determining the levelised cost of fuel (LCOF) – a key economic indicator used for system optimisation – is performed outside OpenModelica using a Python script. The LCOF is defined as the present value of the plant costs expressed in dollar per litre of the fuel produced by the system over its lifetime. The total capital cost of the system is calculated using the n^{th} plant scenario [13] with 30 years plant life, 2 years construction time and 5% discount rate.

The dynamic model described in this paper is available as a part of the SolarTherm repository [14, 15], a free open-source simulation tool providing a platform to researchers to rapidly prototype next-generation CSP designs and perform flexible annual performance simulations. SolarTherm component models were written in OpenModelica and are fully compatible with the Modelica Standard Library (MSL). SolarTherm also has a number of Python scripts wrapped around the OpenModelica engine for pre- and post-processing purposes (e.g. plotting, cost analysis, parametric studies, and optimisation).

RESULTS AND DISCUSSION

The annual simulation of the proposed plant was conducted using TMY3 weather data for Geraldton – a coastal city in Western Australia with relatively high solar radiation and easy access to sea water for growing microalgae. The 'DASSL'and 'homotopy'methods were used as the numerical and non-linear solvers, respectively. A fixed time-step of five minutes was chosen to achieve a satisfactory temporal resolution. The CPU-time for integration of a full-year simulation was ~20 s. A detailed parametric study is carried out to determine the optimal design point of the proposed solar fuel plant from a techno-economic standpoint. Solar multiple (SM) and syngas storage capacity are two key design parameters for the sensitivity analysis of the annual techno-economic performance of the plant. SM is defined as the output of the solar field at design point divided by the field output required to drive the FT plant at its nominal rate. Increasing the SM of a CSP plant represents either increasing the size of the solar field or decreasing the nominal capacity of the useful liquid fuel generated. In this study, it is assumed that the size of the solar field is fixed to avoid re-simulations of the optical performance of the field at different sizes. It should be mentioned that the plant LCOF is considered as the objective for the parametric study in this paper. The technical inputs for the simulation of the solar fuel system are listed in Table 1. It should be noted that the information relating to the transient behaviour of the FT reactor corresponds to a micro-tubular reactor due to its relatively fast startup time as compared to conventional designs [1].

Figure 2 demonstrates the variation of the plant LCOF as a function of the syngas storage at various solar multiples. The black dots on the figure show the minimum LCOF corresponding to each graph (i.e. SM). As seen in this figure, the LCOF tends to decrease as the size of the tank increases up to 16 hours. However, more increase in the syngas storage hours leads to an increase in the LCOF, indicating there is no advantage in going beyond a certain storage volume. The results in Fig. 2 also suggest that it would be advantageous to increase the solar multiple up to 3.5, meaning a too small/large FT unit does no seem to be suitable to achieve a minimised LCOF. Hence, the parametric study shows that a design point with the solar multiple of 3.5 and storage capacity of 16 hours results in an optimum techno-economic performance of the plant with an LCOF of ∼ 3.2 AUD/L. The relatively higher optimal solar multiple observed in the present work as compared to that of a CSP electricity generation plant – which is normally around one to two [18, 19, 20]) – can be attributed to the presence of a set of constraints at the dispatch controller to prevent the FT unit from frequent on/off cyclings, which in turn influenced the optimal size of the FT reactor.

The dynamic results of the key performance variables of the plant over three representative days in the summertime are demonstrated in Fig. 3, assuming a solar multiple of 3.5 and 16 hours of syngas storage. As shown in this figure, due to the linear gradient function considered during the ramping periods, the consumption/production rates at each

TABLE 1. Technical inputs of the solar fuel system used for system-level simulations.

Parameter	Unit	Value
Field design power	MW_{th}	50
Design direct normal irradiance (DNI)	W/m^2	1000
Concentration ratio	suns	1000
Heliostat dimensions	m	6.1 × 6.1 [16]
Number of heliostats	-	1872
Field area	m^2	69661.2
Starting/stopping DNI cut-off level	W/m^2	300
Ramp-up/ramp-down duration at receiver	minutes	30 [3]
Ramp-up/ramp-down/transitioning duration at FT	h	2 [17]

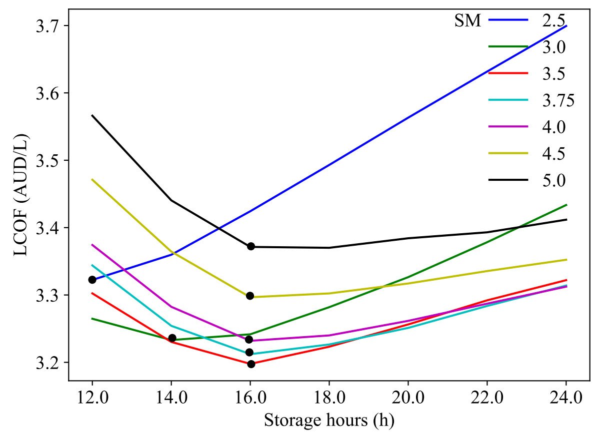

FIGURE 2. Influence of the syngas storage hours and solar multiple (SM) on the plant LCOF with black dots showing the minimum LCOF for each graph.

component (i.e. the solar field, receiver and FT reactor) increase or decrease in a linear manner as functions of the incoming solar power/syngas supply until the start-up/transitioning period is complete. It can also be observed from this figure that the use of syngas storage tank upstream of the FT unit ensures a stable syngas delivery regardless of the fluctuating nature of solar irradiation. Moreover, it can also evidently be seen that based on the one-day-ahead predictive scheduling technique used in this work, the syngas dispatch target flow rate at nights is computed such that the shutdown times of the FT unit is minimised where possible (see the operating control states in Fig. 3).

The performance-related results of the plant at the optimal design point determined through the parametric study are presented in Table 2. As shown in this table, 19.4×10^3 tonnes of syngas is generated from the SCWG+SMR process with ~99 GWh_{th} of CSP delivered to the receiver along with ~17,000 tonnes of algae consumed throughout the year. It should be noted that 7.1×10^3 tonnes of CO_2 is dumped from the receiver in order to condition the syngas for the downstream FT synthesis. The annual fuel production of the system is found to be ~10,900 m^3 with a capacity factor of 71%. The relatively high capacity factor of the system shows the importance of the predictive dispatch controller in minimising the FT reactor shutdowns. The total capital and operational costs of the system are ~162 M-AUD and ~24 M-AUD per year, respectively.

The breakdown of the plant capital costs, annual operational costs, and total annualised costs at the optimal design of the system are presented in Fig. 4. The FT reactor has the highest share of the plant capital cost, followed by the storage tank and the receiver. Furthermore, the algae feedstock has the largest share of the system annual operational costs, followed by the O&M and H_2 costs. Overall, the operational and capital costs constitute 69% and 31% of the

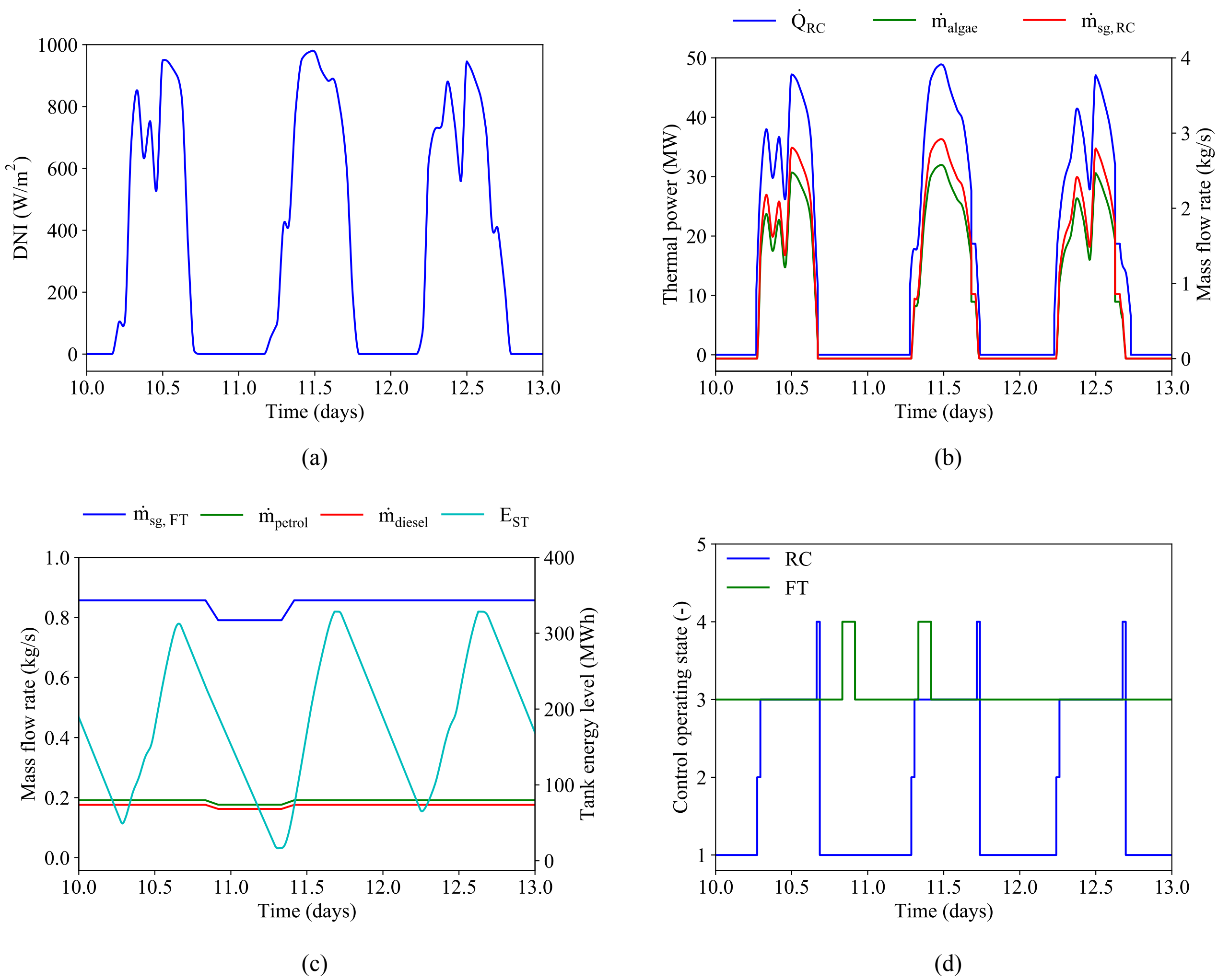

FIGURE 3. Key performance parameters of the plant over three representative summer days: (a) DNI variation, (b) receiver performance, (c) storage and FT performance, and (d) RC and FT operating control states (RC: receiver, sg: syngas, ST: storage).

plant annualised cost, respectively. Finally, the daily and accumulated liquid fuel yield from the plant throughout the simulated year is shown in Fig. 5.

Overall, based on the simulation results demonstrated in the present work, it seems that the real challenge for the industry is to reduce the cost associated with the algae feedstock in order for this technology to be competitive as compared to the conventional petroleum-based fuels. In addition, other opportunities for further cost reduction of the plant include switching to alternative cheaper feedstock, re-using the CO_2 waste to increase the growth rate of algae, and considering other types of reforming process to produce syngas.

CONCLUSIONS

In this work, an energy-based dynamic model of a solar fuel plant based on coupling a CSP-driven SCWG+SMR with a FT reactor is presented. The modelling of the system was carried out using the OpenModelica software based on polynomial performance curves of the main system components (i.e. the gasification and FT plants) derived from detailed steady-state physical models in ASPEN Plus. The economic analysis of the system was conducted using the n^{th} plant scenario method to determine the total cost of the system (including the capital cost, operational cost, and

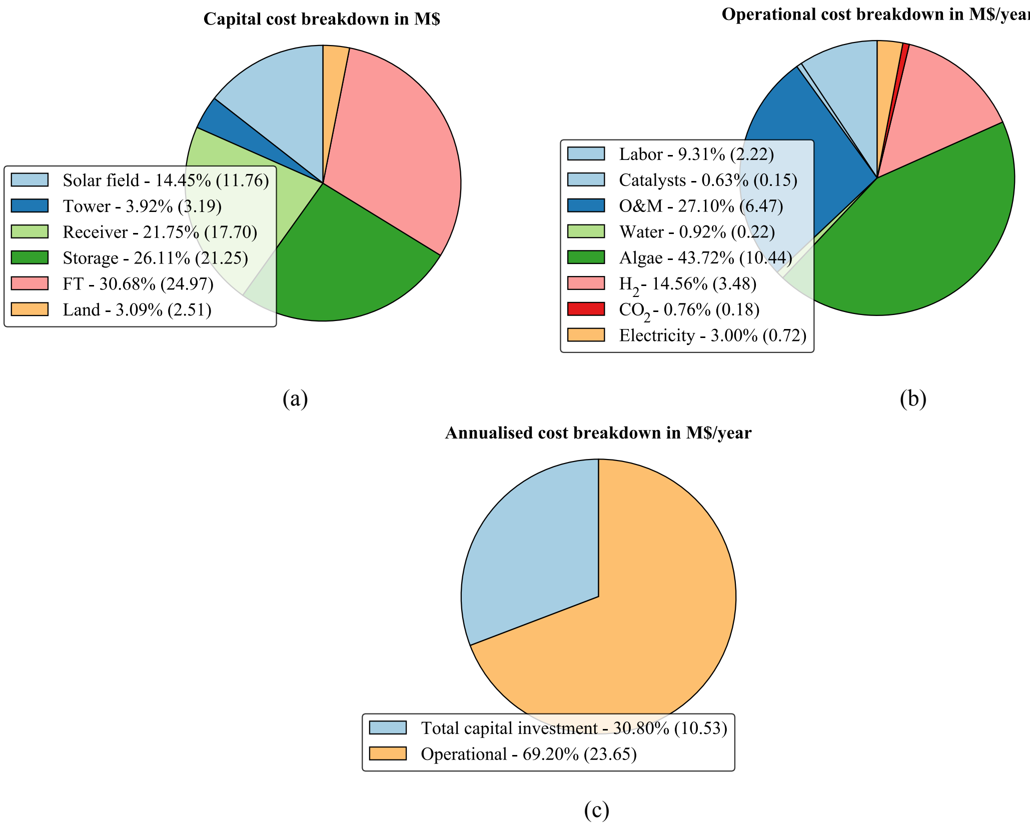

FIGURE 4. The (a) Capital, (b) operational and (c) annualised cost breakdown of the system at the optimal design point.

carbon tax due to CO_2 dumping), and thus the LCOF of the plant. A parametric study of the system was performed by varying key design parameters in order to evaluate the performance of the system from a techno-economic standpoint. The results indicated that a system with a solar multiple of 3.5 and a storage capacity of 16 hours can achieve a

TABLE 2. The system performance-related results at the optimal design point obtained from the parametric study (i.e. SM of 3.5 and storage hours of 16).

Parameter	Unit	Value
CSP delivered to RC	GWh/year	99.1
Algae consumption	$10^3\times$ tonne/year	17.1
H_2 consumption	$10^3\times$ tonne/year	0.4
CO_2 dumped	$10^3\times$ tonne/year	7.1
Syngas produced	$10^3\times$ tonne/year	19.4
Liquid fuel produced	m^3	10939.2
CF	%	71
Total operational cost	million AUD/year	24
Total capital cost	million AUD	162
LCOF	AUD/L	3.2

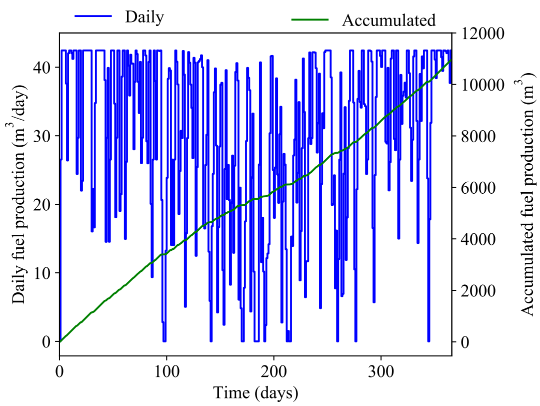

FIGURE 5. Fuel production from the proposed solar fuel plant throughout the year.

minimised LCOF of 3.2 AUD/L (~2.3 USD/L), which is relatively higher than the cost of equivalent petroleum fuels. At this design point, a capacity factor of 71% was obtained, while the total capital and operational costs of the system were 162 M-AUD and 24 M-AUD per year, respectively. Based on the current market, it seems a realistic approach to make the proposed technology competitive is to blend the produced solar liquid fuel with fossil fuel such that emissions reduction can be balanced with the consumer willingness to pay for cleaner fuel. Future development of this work will include exploring the overall annual performance of the presented solar fuel plant under various ramping periods, evaluation of different reforming processes and different downstream syntheses along with a detailed system-level optimisation.

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