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SOLAR ENERGY FOR HYDROGEN PRODUCTION: EXPERIENCE AND APPLICATION IN SOUTH AFRICA

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ABSTRACT

Hydrogen is expected to be a key role player in the future energy market for stationary, mobile and electrical grid balancing applications if produced from renewable energy sources. Hydrogen energy technologies include direct power from fuel cell, storage for intermittent renewable energy, and power-to-gas (P2G) applications. In the last year P2G has been identified as having a large potential with several possibilities in itself: (1) Hydrogen is produced from excess renewable energy and injected directly into natural gas networks. (2) Hydrogen along with a CO_2 emitting source employing the Sabatier process produces synthetic natural gas (SNG). (3) Hydrogen in a bioreactor employing a biocatalyst increases the biogas energy content by reducing CO_2 content. At HySA Infrastructure research focus is on hydrogen production from renewable energy as the central technology for the enhancement of the different hydrogen energy prospects. This paper will focus on presenting results from the recently upgraded solar-to-hydrogen system at the HySA Infrastructure center at North-West University. The previous small-scale solar-to-hydrogen system is upgraded to South Africa's first commercial scale renewable hydrogen production plant. The main purpose of the upgrade is to increase the hydrogen production capacity and improve system performance. System performance includes the increase of overall system efficiency and to reduce the cost of hydrogen. The paper includes prospects of renewable hydrogen in South Africa, and how solar-to-hydrogen research falls into the bigger picture of hydrogen in South Africa.

INTRODUCTION

The transition towards a cleaner and more sustainable energy system requires large scale employment of renewable energy sources. Renewable energy sources have low life cycle carbon emissions but also have intermittent characteristics. To benefit from the low carbon emitting power production capable with renewable energy sources, the problem of electricity demand not being in line with production is a major stumbling block [1]. The purpose of renewables for future energy systems is low carbon emissions but also a sustainable supply. The energy source should be available at all times without restrictions [2]. Due to its intermittency renewable energy requires a larger net generation capacity for a higher penetration of renewable energy [3]. This larger net generation capacity allows access energy to be produced during times of surplus and can then be used during times when there is a shortfall. Thus, in order to be more reliable intermittent renewable energy sources require a form of energy storage.

A review of energy storage technologies for electric power applications [4], looked at several storage technologies including: flywheel, super capacitor, hydrogen, pumped storage, liquid piston pneumatic, and compressed air pneumatic, with the conclusion being that hydrogen energy storage is not yet viable mainly due to cost. A more recent review on redox flow batteries (RFB) compared the same storage technologies with RFB [5]. The conclusion is that RFB is a promising storage technology. It however is still in a research phase with much promise. A comparison of available energy storage technologies are provided in Figure 1 [6].

Flywheel energy storage, double layer (super) capacitor, and superconductor magnetic energy storage have only seconds to minutes of storage. All the battery technologies (LA, Li-ion, RFB, NaS) have storage duration of hours to days in limited capacity. Pumped hydro and compressed air energy storage have large capacity possibilities and durations of a couple of days but require sites which are limited in South Africa. Hydrogen and SNG have large capacity potential capable of long term storage and seasonable balancing of intermittent renewable energy sources [2]. Hydrogen storage in [6] refers to the P2G applications which is the term given to the conversion of electrical power from excess renewable energy into the chemical energy carriers, hydrogen and SNG. P2G is a way to store and transport energy and recycle CO_2.

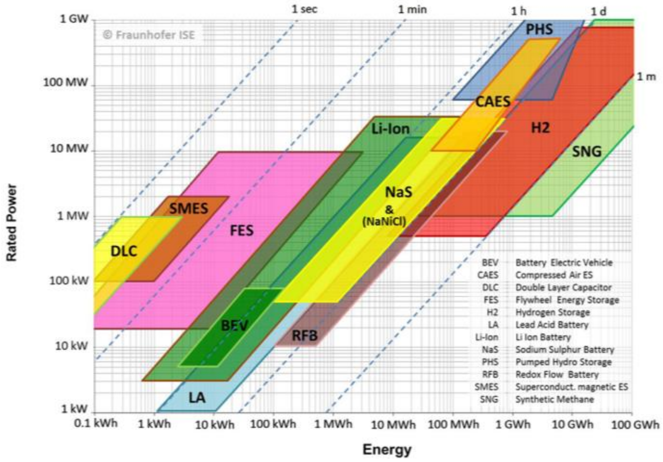

Figure 1 Comparison of energy storage technologies [6]

P2G is based on the production of hydrogen through electrolysis. Hydrogen is then utilised in various technologies under the P2G umbrella. The following P2G technology options are available:

Chemical methanation via the Sabatier process: the methanation route to P2G is implemented via the Sabatier reaction. In the Sabatier reaction CO_2 in the presence of a catalyst reacts with hydrogen to form CH_4 and H_2O.

The water from the reaction is extracted and used as is or in the electrolysis process to from H_2 and O_2 [7].

Biological methanation (biogas enrichment): In this technology, the Sabatier reaction takes place in reactors filled with bacteria and archaea which are used to convert again hydrogen and CO_2 into CH_4 [7].

Energy storage in the natural gas network: Hydrogen produced from excess renewable energy is injected directly into the natural gas grid.

Industrial hydrogen feed and *hydrogen fuelling* are two technologies where hydrogen produced from excess renewable energy is used in its pure form to supply the existing industrial and laboratory requirements and also fuel for fuel cell vehicles [7]. Figure 2 gives a schematic overview of the P2G applications.

POWER-TO-GAS IN SOUTH AFRICA

P2G depends on the successful integration of renewable energy sources and hydrogen production technology. In a recent article [8], a platform for hydrogen production and storage was discussed for the telecom market. Hydrogen production from renewables in South Africa is shown to be successful with technologies and experts capable of meeting any P2G requirements. From the P2G technology options, *chemical methanation*, *biological methanation*, *industrial hydrogen feed*, and *hydrogen fuelling* are viable technologies that can be considered for South Africa. Storage in the natural gas network might be an option in future with the South Africa government gas utilisation master plan investigating the necessary infrastructure to open up gas prospect for South Africa. The master plan is considering the

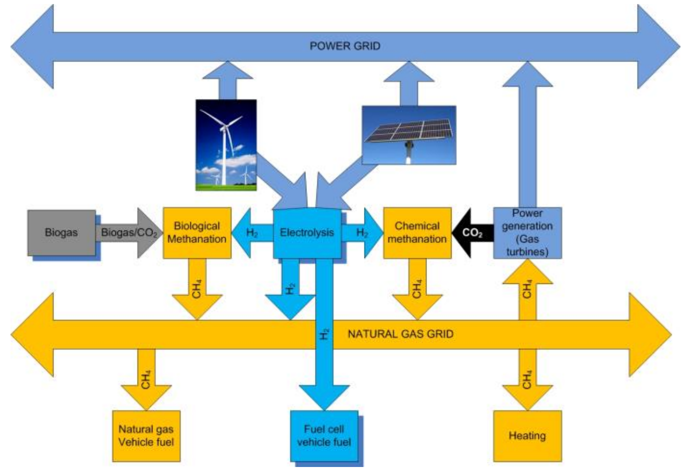

Figure 2 Schematic overview of power-to-gas

gas finds in Mozambique and also in the Karoo. Also being considered is the conversion of the open cycle gas turbines that are either operational or under development in Saldanha Bay, Mossel Bay, Coega in Port Elizabeth, Durban and Richards Bay to closed-cycle gas turbines fuelled using gas [9]. Figure 3 provides technologies, potential clients and benefits of a P2G platform in South Africa.

Commercial Platform for Power-to-Gas in Africa

Products	Clients: CNG consumers	Clients: SASOL	Clients: ESKOM	Clients: Egoli gas	Clients: CNG group of companies	Clients: Waste water treatment works	Clients: Waste disposal facilities	Benefits: Waste mamangement	Benefits: CO2 Reduction	Benefits: Reduce cost of fuel	Benefits: Reduce cost of energy	Benefits: Reduce load on ESKOM
Methane production	X	X	X	X	X				X	X	X	X
Biogas enhancement	X	X	X	X	X	X	X	X	X	X	X	X
Hydrogen production		X	X	X					X			X
Hydrogen/methane storage				X	X	X	X		X			X

Figure 3 Platform for Power-to-Gas in Africa

Although a gas network is not available there is the prospect of implementing *chemical and biological methanation* at biogas plants and close to CO_2 sources such as SASOL and coal fired electrical power plants, producing SNG. The SNG can be burned with current fossil fuels, used in closed-cycle gas turbines at the site of gas generation, and used as fuel for transportation in CNG compatible vehicles. *Industrial supply* and *hydrogen fuelling* are already possibilities with the production of hydrogen alone.

HYDROGEN PRODUCTION

P2G is based on the production of hydrogen from excess renewable energy sources. A study on renewable energy in South Africa [10] shows that South Africa has an abundance of renewable energy, and more specifically solar energy. Although solar energy is not the only possibility, viable wind energy sites are limited to certain coastal areas [11]. Solar energy is however abundant all across South Africa [12]. Intermittent renewable energy sources, more specifically wind and solar photovoltaic, are considered to be the only viable solutions for renewable hydrogen production via electrolysis.

The production of hydrogen via water electrolysis is based on two main water electrolysis technologies. Alkaline technology is the most common technology used due to their relative low cost, durability and maturity. Proton exchange membrane (PEM) technology is the most suitable alternative to alkaline technology. PEM technology is still under development although commercial units up to 50 kW_e are already commercially available. Figure 4 gives the schematics of the operating principles of alkaline and PEM water electrolysis.

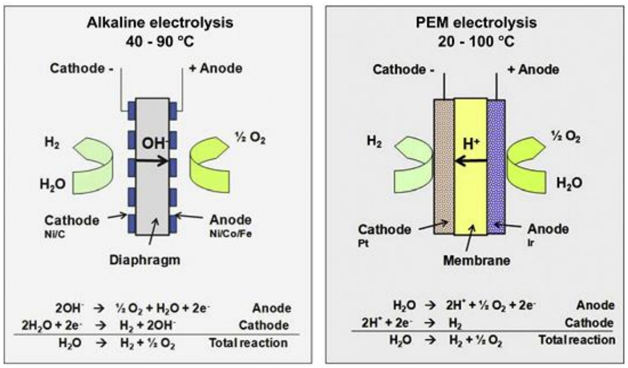

Figure 4 Operating principle of alkaline and PEM water electrolysis [13].

A review article on PEM water electrolysis [13], conclude that PEM based electrolysis is the preferred technology for hydrogen production from intermittent renewable energy sources. PEM-technology is a solid state system whereas alkaline has a liquid electrolytes requiring recycling. The solid membrane results in ultra-high pure hydrogen being produced at the Cathode requiring no purification which is needed by alkaline systems. PEM systems have a small footprint due to the high current densities which are possible; > 1 A/cm^2 compared to 0.4 A/cm^2 by an alkaline system. PEM technology is capable of fast response time and start-up/shut-down characteristics and can tolerate large variations in load. All these characteristics make PEM technology the ideal technology for implementation with intermittently available sources of electricity (renewable and off-peak grid). A further benefit of the PEM technology unique to South Africa is the use of Platinum in the catalysts. South Africa accounts for approximately 80 % of the world's total annual platinum production and contains an estimated 88% of the world's platinum reserves [14].

SOLAR-TO-HYDROGEN SYSTEM UPGRADE

At the Potchefstroom campus of the North West University the solar to hydrogen system has been operating from early 2013. The purpose of the first generation system was proof of concept and consisted of 6 kW_p photovoltaic (PV) panels, 30 kWh battery storage, 2.3 kW_e PEM electrolyser capable of producing > 0.5 kg hydrogen per day. The Generation 1 solar-to-hydrogen system layout is given in Figure 5 [16].

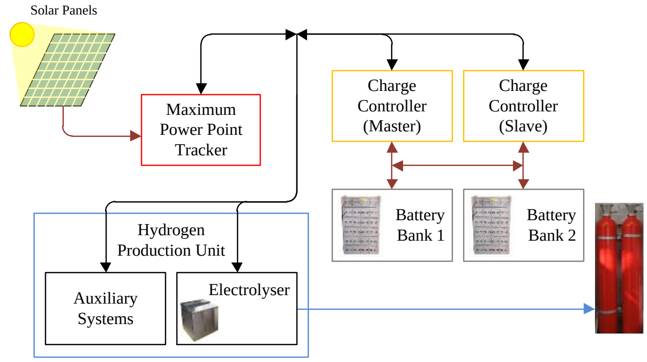

Figure 5 Generation 1 solar-to-hydrogen system

The Generation 1 proof of concept system hydrogen production capacity was approximately 0.5 kg (STP) per day. During March of 2014 the system was upgraded in order to produce more than 2 kg (STP) hydrogen per day. The PV system capacity was increased to 15 kWp, the battery storage increased to 90 kWh and the electrolyser increased to a 7kW_e unit having higher production rate. The Generation 2 solar-to-hydrogen system layout is given in Figure 6.

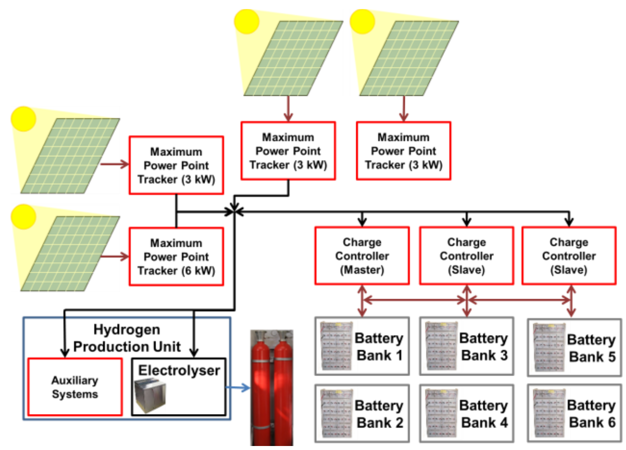

Figure 6 Generation 2 solar-to-hydrogen system

The Generation 2 system is a commercial scale hydrogen production facility supplying ultra-high purity hydrogen. A photo of the upgraded PV system is given in Figure 7 and the battery storage and power electronics in Figure 8.

Figure 7 Gen 2 solar-to-hydrogen 15 kWp PV panels

Battery storage in this system is selected as a trade-off between the cost of a PEM electrolyser that can produce the required hydrogen during the hours of sufficient sunshine and a smaller PEM electrolyser where the system includes battery storage to produce hydrogen past the hours of sufficient sunshine. In large scale systems (>20 kW) buffer storage for the renewable energy source is omitted.

Figure 8 Gen 2 solar-to-hydrogen power converters and 90 kWh battery storage

SYSTEM PERFORMACE

A previous work [16] presents the performance of the Gen 1 system. Maximum system efficiency achieved was 29.6 %. System efficiency is determined from the energy delivered by the PV panels and the energy content of the hydrogen. A Sankey diagram for the Gen 1 system is given in Figure 9 [16].

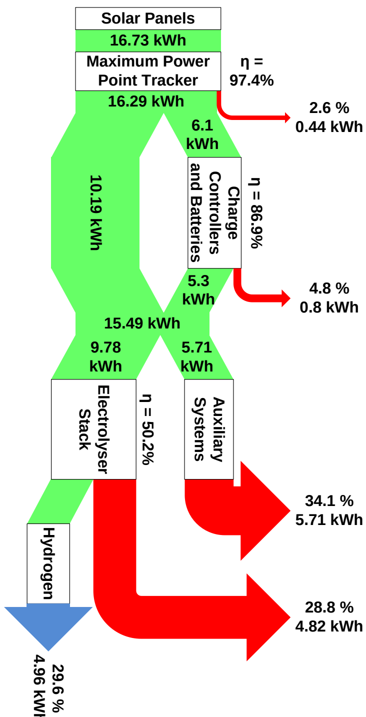

Figure 9 Gen 1 Sankey diagram

A large loss was reported due to auxiliary systems. One of the recommendations was that an increase in system capacity would reduce these losses since the auxiliaries such as fans, heaters and control system power usage would remain the same for the larger system with larger capacity. Increasing the efficiency and commercial scale supply was the motivation for the upgrade. A Sankey diagram for the Gen 2 system is provided in Figure 10. From the figure an efficiency of close to 38 % is given. From various tests the efficiency ranged between 36 and 38 %, a considerable increase from the Gen 1 system 29 %. The performance of the system includes data that starts and stops at the same battery state of charge (SOC) values.

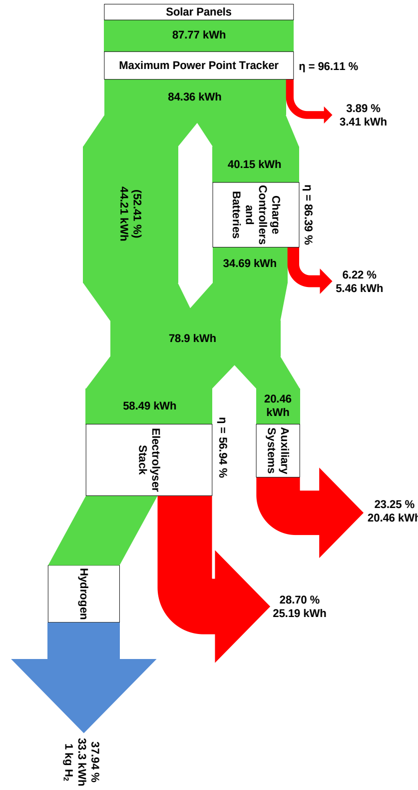

Figure 10 Gen 2 Sankey diagram

For this specific day the battery SOC was at 90 %, thus recorded data was used until the SOC was again 90 % the following day. The solar irradiation and battery SOC for this period is given in Figure 11.

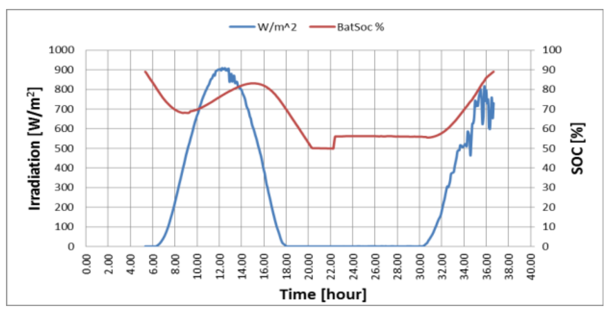

Figure 11 Solar irradiation and battery SOC

Figure 12 gives the power provided by the PV, the power used by the electrolyser and the power supplied by the batteries.

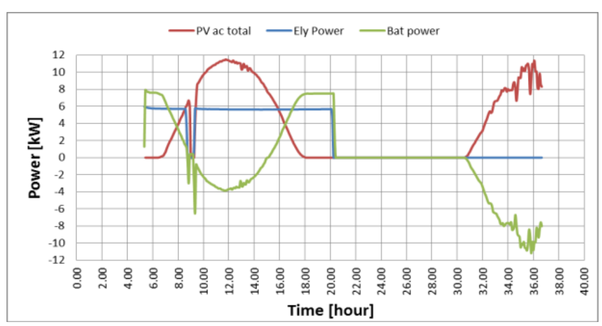

Figure 12 PV, electrolyser and battery power

Battery power is positive when supplying the load and negative when charging from the PV. Figure 12 shows the electrolyser starting up just after 5:00. Immediately battery power supplies the load. At approximately 7:00 the PV plants start to supply and the battery contribution reduces until 9:00 when PV surpasses the load requirement and supplies the load and charges the battery. Around 15:00, PV power reduced such that the batteries again supplied part of the load, until 18:00 when all power was again supplied via batteries. During this experiment the electrolyser was shut down for about one hour. The electrolyser operated until approximately 20:00. Battery SOC is approximately 50 % at this time. Approximately 1.4 kg hydrogen was produced during the 15 hours of operation. Figure 12 shows that the electrolyser power (blue) reduces with time until it reaches a steady state after a couple of hours. Efficiency and voltage over time is given in Figure 13.

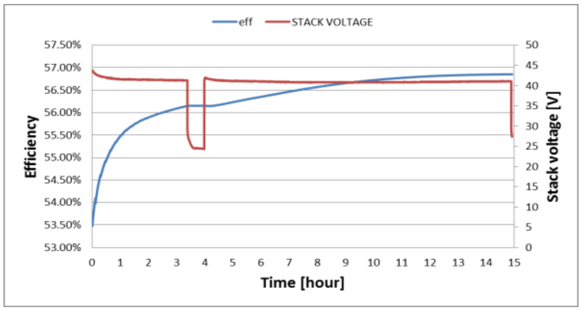

Figure 13 Electrolyser efficiency over time

It is shown that the efficiency at the start of operation is low, approximately 53.5 %, and increases to close to 57 % after a few hours of operation. This is attributed to the temperature of the system. From literature [15], it is shown that the electrolyser takes time to reach its normal operating temperature and while at lower temperatures the electrolyser operates at lower efficiency. Although the PEM electrolyser is suited for intermittent operation, thermal management is one of the issues resulting in lower efficiencies. To improve on system efficiency it is preferred that the electrolyser be operating for long periods of time in order to reach operating temperature. The electrolyser used in the solar-to-hydrogen system is designed to have a long lifetime thereby sacrificing efficiency. The maximum efficiency is around 57 %, although from literature [15], it is shown that PEM electrolysers can operate with efficiencies as high as 80 %. Taking this into consideration the system efficiency can be further improved with a higher efficiency electrolyser. Figure 14 gives the Sankey diagram for a theoretical situation where the electrolyser efficiency is assumed to be 80 %. Overall system efficiency increases to approximately 53 %, considerably higher than the 38 % with the current electrolyser unit, and a long way past 29 % which the previous Gen 1 system could achieve.

PV panels require cleaning on regular basis. To quantify the effect of cleaning, one 3 kW system (12 panels) is cleaned, clearly visible in Figure 15, to measure the gain in efficiency.

Figure 16 gives the measured output for the three 3 kW systems before cleaning. The three systems have almost exact power outputs which are expected as these systems are mounted at the same angle on the same roofs experiencing the

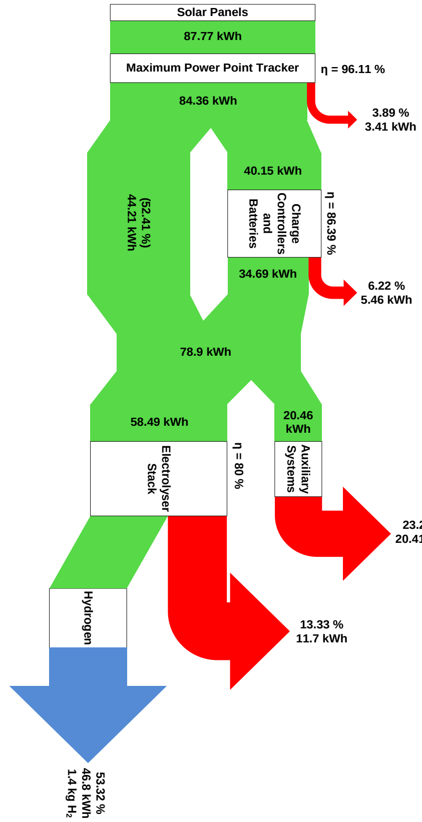

Figure 14 Gen 2 Sankey diagram - high efficiency electrolyser

Figure 15 One set of 3kW PV panels cleaned

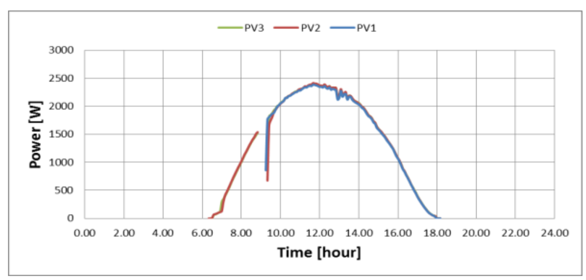

Figure 16 Output for the 3 x 3kW systems before cleaning

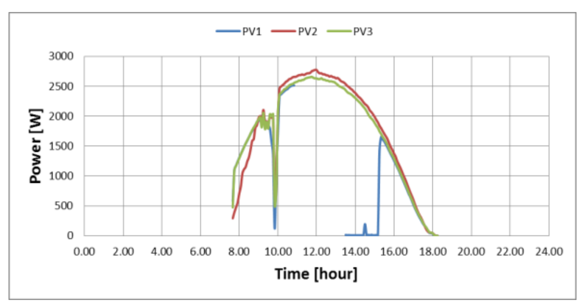

Figure 17 Output for the 3 x 3kW systems after cleaning

same irradiation. Figure 17 gives the output after cleaning. The increase in output from the cleaned system (PV2) is clearly visible. PV2 started off having a lower output due to the cleaning of the panels which started just after 7:00. Because this is an island system where the PV output is dependent on the load, PV1 was shut off as the irradiation increased to ensure that PV2 and PV3 would be producing maximum power. The peak output of PV2 was approximately 4.3 % more than that of PV1 and PV3 throughout the day. For the 3 kW system the increase in output is around 115 W. In total that results in total increase of 576 W if the entire 15 kW system is cleaned.

CONCLUSION AND FUTURE WORK

The solar-to-hydrogen system at the Potchefstroom campus of the North-West University has been in operation for more than two years now. The Gen 1 proof of concept system was successfully operated, producing approximately 0.5 kg (STP) ultra-high purity hydrogen per day. The Gen 1 system proved the concept of producing hydrogen from renewable energy sources, in this case solar PV energy due to site considerations. Due to the success of the Gen 1 proof of concept system, it was upgraded to the Gen 2 commercial scale system capable of producing approximately 2.5 kg (STP) ultra-high purity hydrogen per day. Analysis shows an increase of system efficiency from 29 % to 38 % by upscaling. A further increase in system efficiency would be possible by using an electrolyser with efficiency of 80 % that would result in an overall system efficiency of 53 %. These high efficiency electrolysers are already commercially available. Further efficiency increases can be obtained by further up scaling. In large scale systems battery storage would be omitted and related energy losses omitted which would result in system efficiencies >58 %. Auxiliary system contribution to losses will be reduced resulting in realistic system efficiencies above 60 %. These efficiencies consider the final product to be hydrogen. Round trip efficiencies would be approximately 35 % as is reported in [6]. This does not compare good with most other energy storage technologies. Hydrogen storage does however have comparable cost to other electro-chemical storage technologies when considering the life of the plant. Further benefits of a hydrogen system are the small footprint resulting from the considerable energy density, and that it can be used as fuel for transportation. Additional increase of input energy of 4.3 % is possible through the cleaning of the PV panels. Further up scaling of the current system is however not viable.

The true advantage of hydrogen however lies in P2G applications which are why system efficiency considers the end product to be hydrogen. Power-to-gas relies on the successful and efficient production of hydrogen from renewable energy sources. The generation 2 solar-to-hydrogen system is proof that hydrogen can be efficiently produced from solar energy. It is also noted that higher system efficiencies can be achieved through up scaling of the system and by implementing higher efficient electrolyser stacks. Power-to-gas in South Africa depends on further research in the implementation of hydrogen from renewable sources in a power-to-gas application. Although power-to-gas applications in South Africa are limited, there are possibilities that need to be investigated.

Ongoing work includes investigating and identifying power-to-gas applications in South Africa. Future work includes implementing power-to-gas on small scale and later on large scale with renewable hydrogen production as the major driver.

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