Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Xi'an21
18th–20th October, 2021

www.gpps.global

GPPS-TC-2021-0209

Range of application for a self-sufficient energy system with hydrogen as energy carrier in remote areas

Tin Jurisic
Technical University of Munich
Department of Mechanical Engineering
Institute of Plant and Process Technology
tin.jurisic@tum.de
Garching, Bavaria, Germany

Sebastian Rehfeldt
Technical University of Munich
Department of Mechanical Engineering
Institute of Plant and Process Technology
sebastian.rehfeldt@tum.de
Garching, Bavaria, Germany

Michel Kneller
ILF Beratende Ingenieure GmbH
michel.kneller@ilf.com
Munich, Bavaria, Germany

Harald Klein
Technical University of Munich
Department of Mechanical Engineering
Institute of Plant and Process Technology
harald.klein@tum.de
Garching, Bavaria, Germany

ABSTRACT

A self-sufficient hydrogen energy system provides energy directly and by converting electricity into hydrogen and reconverting it when needed. In order to get a broader understanding of the technical feasibility for this concept, power, storage and size ranges of the system need to be elaborated. The subsystems such as renewable energy source, hydrogen generation, storage and reconversion are discussed. In addition, the technology evaluation drawn from the state-of-the art form the basis for the energy system concept. Taking specific requirements for the off-grid system into consideration, the process is modeled for the stationary case providing the power outputs for hydrogen generation and reconversion as well as storage capacities. A comparison to conventional self-sufficient energy systems such as diesel generators is made and the range of application for containerized hydrogen self-sufficient energy systems is narrowed down.

INTRODUCTION

Aiming at mitigating climate change by reducing carbon emissions as stated in the Paris Agreement of 2015, hydrogen is increasingly seen as promising clean energy carrier of the future and part of the overall solution. Many industrialized countries push the needle on establishing hydrogen economies, such as Germany with the goal to install 5 GW of electrolyzer capacity by 2030 (Federal Ministry for Economic Affairs and Energy (BMWi), 2020). In parallel to achieving the climate targets, challenges with electrification in rural areas still remain. More than 1 billion people worldwide have no access to electricity, hindering technological, economical and social progress in affected regions (Ritchie and Roser, 2019).

Hydrogen can be a key element in enabling remote and off-grid locations to cover their energy demand independently while counteracting climate change. Through electrolysis powered by renewable energy, green hydrogen is generated and stored at times when renewable energy production exceeds energy demand. In case the renewable energy is insufficient to cover energy demand, the stored hydrogen can be reconverted with a fuel cell, thereby covering the differential energy demand (Lamb et al., 2020). Current research on self-sufficient energy systems focuses mainly on primary storage with batteries as elaborated by Puranen et al. (2021) or Gstöhl and Pfenninger (2020). This work on the other hand introduces a concept for a compact energy system with hydrogen as primary energy carrier for short as well as long-term storage. Even though the need for a battery in this system cannot be eliminated fully, the goal is to keep the battery size to a minimum and therefore it is neglected in the further approach.

The technical and economic feasibility of such a system depends on many factors such as availability of renewable energy and water, energy demand, size and component costs. In order to compare hydrogen energy systems under different circumstances, the determination of process and design parameters is necessary. Figure 1 depicts the main components of a hydrogen energy system while the corresponding energy and process streams are defined in Table 1.

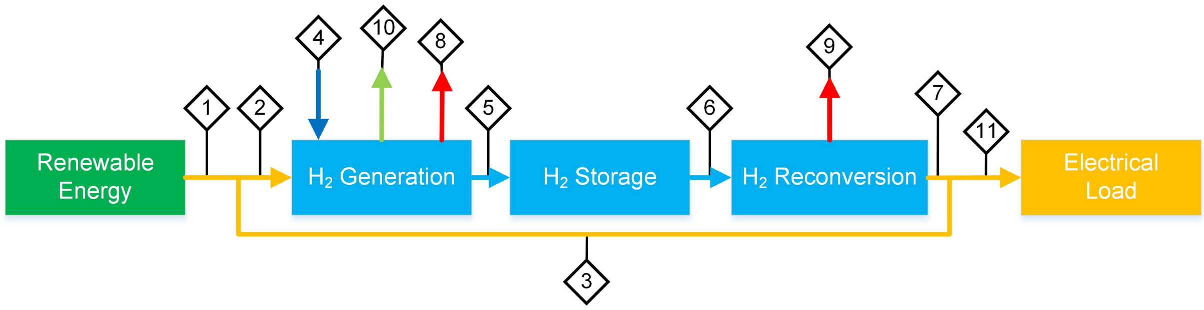


Figure 1 Block Flow Diagram of a Hydrogen Energy System with streams 1 to 11 from Table 1.

Table 1 Stream Table of a Hydrogen Energy System.

Stream	1	2	3	4	5	6	7
Type	Electrical	Electrical	Electrical	Water	Hydrogen	Hydrogen	Electrical
Variable	P_{RE} in kW	$P_{\mathrm{H2}Gen}$ in kW	$P_{\mathrm{RE,Load}}$ in kW	$\dot{V}_{\mathrm{W}}$ in $\frac{\mathrm{l}}{\mathrm{h}}$	$\dot{V}_{\mathrm{H2}Gen}$ in $\frac{\mathrm{Nm}^3}{\mathrm{h}}$	$\dot{V}_{\mathrm{H2}Store}$ in $\frac{\mathrm{Nm}^3}{\mathrm{h}}$	$P_{\mathrm{H2}Re}$ in kW

Stream	8	9	10	11
Type	Heat	Heat	Oxygen	Electrical
Variable	$\dot{Q}_{\mathrm{H2}Gen}$ in kW	$\dot{Q}_{\mathrm{H2}Re}$ in kW	$\dot{V}_{\mathrm{O2}}$ in $\frac{\mathrm{Nm}^3}{\mathrm{h}}$	P_{Load} in kW

Any form of renewable energy can drive the process and supply energy to cover the electrical load and generate hydrogen. In the past, solar photovoltaic energy was mainly utilized for off-grid applications due to low costs and high on-site availability (Akikur et al., 2013; Kavlak et al., 2018). Wind energy and hydro energy can provide an alternative if favorable site conditions are present. Moreover, hybrid concepts with two or more renewable energy sources as described by Bhandari et al. (2014) bring advantages to renewable energy generation, but face challenges with regards to techno-economical feasibility and complexity of the overall system (Fathima and Palanisamy, 2015). Hydrogen generation, storage and reconversion as shown in Figure 1 replace the role of a conventional battery storage. The hydrogen is generated by low-temperature electrolysis, which splits water to oxygen and hydrogen at temperatures below 100 °C (Zhang, 2020).

There are three low-temperature electrolysis technologies to consider for off-grid hydrogen energy systems deriving their names based on the electrolyte used. A technology still emerging is anion exchange membrane electrolysis (AEMEL). The major advantage of AEMEL is the utilization of transition metals instead of noble metals as catalysts leading to reduced costs (Vincent and Bessarabov, 2018). Furthermore, it combines advantages of high current densities from Proton Exchange Membrane electrolysis (PEMEL) with stability of lower-cost catalysts and flow field materials of liquid alkaline electrolysis (AEL). AEL is the most established electrolysis technology and normally produces hydrogen at atmospheric pressure at low current densities, but with high efficiency. Due to certain drawbacks of AEL, PEMEL was developed with charateristics such as increased current density, reduced ohmic losses across the cell and pressurized operation through the utilization of a solid polymer electrolyte. More expensive construction materials due to the locally acidic environment of the membrane are viewed as negative aspects of PEMEL (Ayers et al., 2019). Besides the core functionality of splitting water to hydrogen and oxygen, the hydrogen generation unit also purifies the feed water for the electrolysis and removes oxygen and water traces in the generated hydrogen in order to ensure high-purity hydrogen (Tong et al., 2020; Ligen et al., 2020).

In the next step, hydrogen is stored and subsequently released to a fuel cell for reconversion to electrical power based on the load and power from renewable energy. The hydrogen storage system can be carried out with compression in gas cylinders, liquefaction in cryogenic tanks, storage in metal hydride alloys, adsorption onto large specific surface area-materials and chemical storage in covalent and ionic compounds. Among them, compressed hydrogen is the most common method to store hydrogen even though it is not considered the cheapest one (Sdanghi et al., 2019). Nevertheless, for a hydrogen energy system as shown in Figure 1, compressed hydrogen is a favorable option due to the small number of required components and the possibility to generate compressed hydrogen already from electrolysis. Moreover, if storage pressures remain below the hydrogen generation outlet pressure an additional compressor is not needed.

At times of high electrical energy demand or absence of power from renewable energy, hydrogen reconversion via fuel cell provides additional power to cover the load. Due to the high power density of approximately 1 $\frac{\mathrm{kW}}{\mathrm{kg}}$, high durability and robustness, proton exchange membrane fuel cells (PEMFC) are favorable for stationary applications (Santangelo and Tartarini, 2018; Kurzweil, 2016). Another type is the solid oxide fuel cell (SOFC), which has become commercially available at a small scale (up to 3 kW) over the last few years. A special feature of SOFCs is the possibility of reverse operation. Efforts to further research this concept are on their way and promise a positive development of SOFC in the future (Lymperopoulos et al., 2019). Major drawbacks of SOFCs are related to the high operating temperatures of up to 1000 °C, which in particular affect the long-term temperature resistance of the materials and gaskets as well as the thermal stress within the system (Kurzweil, 2016).

METHODOLOGY

In order to evaluate and compare energy systems, characteristic parameters such as energy and power density, size and weight of the system need to be determined. Using the block flow diagram from Figure 1 as starting point, the process and energy streams are calculated depending on the electrical load P_{Load} and the available power P_{RE} from renewable energy. The difference of these two values is crucial for the process calculation and defined in the following as power difference ΔP:

$$\Delta P = P_{\text{RE}} - P_{\text{Load}} \tag{1}$$

If ΔP is positive, the surplus power $P_{\text{H2}Gen}$ is used to generate hydrogen, otherwise ΔP is negative and the electrical load P_{Load} is higher than the available renewable energy requiring hydrogen reconversion power $P_{\text{H2}Re}$ to equalize $P_{\text{Re,Load}}$ and thereby covering the full electrical load. In case ΔP equals zero, the electrical load is solely covered by the renewable energy source while no hydrogen generation or reconversion is active. Based on this operating philosophy and input data on hydrogen generation and reconversion efficiency, the other streams can be calculated. In a first step, it is assumed that ΔP is the single parameter determining the hourly hydrogen production $\dot{V}_{\text{H2}Gen}$ or, respectively, the hourly hydrogen required for reconversion $\dot{V}_{\text{H2}Gen}$. It is considered that ΔP has to be above the minimum load threshold for hydrogen generation $P_{\text{H2}Gen_{min}}$, which depends on the specific electrolysis technology (Wulf et al., 2018). The hydrogen generation $\dot{V}_{\text{H2}Gen}$ is determined by means of ΔP, the LHV_{H2} and the efficiency $\eta_{\text{H2}Gen}$ of the hydrogen generation:

$$\dot{V}_{\text{H2}Gen} = \frac{\Delta P \cdot \eta_{\text{H2}Gen}}{LHV_{\text{H2}}} \tag{2}$$

By determining the hourly hydrogen generation, the water demand $\dot{V}_{\text{W}}$ can be derived using the stoichiometric chemical equation for electrolysis (see Equation (3)) and the molar masses of the involved elements. Assuming an ideal process, the water demand $\dot{V}_{\text{W}}$ is estimated to be approximately 9 liters of deionized water per kilogram of hydrogen produced. Moreover, the oxygen output $\dot{V}_{\text{O2}}$ is 8 times higher than the hydrogen output per kilogram.

$$\text{H}_2\text{O} \longrightarrow \text{H}_2 + \frac{1}{2}\,\text{O}_2 \tag{3}$$

However, if varying feed water qualities and the corresponding demineralization process are considered, the typical water consumption ranges from 18 kg to 24 kg of water per kilogram of hydrogen (IRENA, 2020). If water consumption for cooling, indirect water consumption embodied in electrical energy and in material and equipment of electrolyzers as well as indirect water consumption embodied in waste disposal are taken into account, the overall water consumption depends on the energy source utilized. For an exemplary case study analyzing hydrogen export from Australia the water consumption varies from 20 liters if wind electricity is used to 130 liters if the elecrtrical power is supplied by the grid. For hydrogen produced by photovoltaic power 40 liters of freshwater are required for one kilogram of hydrogen (Shi et al., 2020).

The thermodynamic irreversibilities in the electrolysis process due to water vapor contained in the hydrogen and oxygen flows decrease the efficiency of hydrogen generation. Also, the lower temperature and pressure of the supply water with regards to the operational set points as well as the thermal losses due to convection and radiation reduce the efficiency of the process (Ursua et al., 2012). An additional cooling cycle is required to remove the heat from the hydrogen generation process $\dot{Q}_{\text{H2}Gen}$ in order to maintain desired operating conditions. Equation (4) determines the heat dissipation from the hydrogen generation process assuming all efficiency losses are in the form of heat.

$$\dot{Q}_{\text{H2}Gen} = (1 - \eta_{\text{H2}Gen}) \cdot \Delta P \tag{4}$$

Analogous to the calculation of the hydrogen generation, the hydrogen required for reconversion $\dot{V}_{\text{H2}Store}$ is calculated by means of the ΔP, the efficiency of the hydrogen reconversion $\eta_{\text{H2}Re}$ and the LHV_{H2}:

$$\dot{V}_{\text{H2}Store} = \frac{-\Delta P}{\eta_{\text{H2}Re} \cdot LHV_{\text{H2}}} \tag{5}$$

As assumed above for the hydrogen generation, the generated heat from the exothermal reaction in the fuel cell $\dot{Q}_{\text{H2}Re}$ fully dissipates as heat (Akinyele et al., 2020), hence it is calculated by:

$$\dot{Q}_{\text{H2}Re} = -(1 - \eta_{\text{H2}Re}) \cdot \Delta P \tag{6}$$

Due to the targeted small-scale application of the hydrogen energy system, hydrogen storage is assumed as a pressurized tank with absolute storage pressures below 50 bar and without additional compressor. As a result of this, the volume $V_{\mathrm{H2}Store}$ of the hydrogen storage can be determined by the ideal gas law taking the hydrogen storage pressure $p_{\mathrm{H2}Store}$, the mass of hydrogen stored m_{H2}, the specific gas constant for hydrogen R_{H2} and the storage temperature $T_{\mathrm{H2}Store}$ into account (Züttel, 2003; von Böckh and Stripf, 2015):

$$p_{\mathrm{H2}Store} \cdot V_{\mathrm{H2}Store} = m_{\mathrm{H2}} \cdot R_{\mathrm{H2}} \cdot T_{\mathrm{H2}Store} \tag{7}$$

The most important result for the further optimization of the system is the hydrogen balance ΔE_{H2}, which is defined as the sum of the difference between the hydrogen produced and the hydrogen required for reconversion for each time interval Δt during the observation period t_{End}:

$$\Delta E_{\mathrm{H2}} = \sum_{t=0}^{t=t_{End}} (\dot{V}_{\mathrm{H2}Gen,t} - \dot{V}_{\mathrm{H2}Store,t}) \cdot \Delta t \tag{8}$$

If the hydrogen balance ΔE_{H2} is positve, more hydrogen was produced than required by the hydrogen reconversion, which indicates an oversized system and the potential to reduce the power P_{RE} of the renewable energy source and the hydrogen generator. If the hydrogen balance ΔE_{H2} is negative, the power P_{RE} from renewable energy needs to be scaled up in order to provide sufficient power for the hydrogen generation. While the load P_{Load} remains the same, the power $P_{\mathrm{H2}Gen}$ for hydrogen generation is adjusted according to the hydrogen balance ΔE_{H2}. In particular, the power P_{RE} of the renewable energy is iteratively increased if $\Delta E_{\mathrm{H2}} < 0$ or decreased if $\Delta E_{\mathrm{H2}} > 0$ for time intervals when renewable energy is available. Once the hydrogen balance ΔE_{H2} equals zero, the optimal process design is found by means of minimum rated power for hydrogen generation. Depending on this result and the dynamics of hydrogen generation and reconversion, the necessary volume to store hydrogen at a absolute pressure of $p_{\mathrm{H2}Store} = 30$ bar and a temperature of $T_{\mathrm{H2}Store} = 20$ °C are calcuated. The rated power of the fuel cell is defined by the peak load of the electrical consumer. For the calculation, constant efficiency of the hydrogen generation and reconversion is assumed as well as no electrical energy losses by electrical power conversion (e.g. rectifier, inverter).

Having sized the required hydrogen generation power, the storage volume and the reconversion power, the volume and weight of the system needs to be assessed taking into account commercially available hydrogen technology. The characteristics of the components applied in the sizing calculation are summarized in Appendix A. All possible configurations based on the considered equipment are evaluated for specific loads of remote locations in order to define the range of application of self-sufficient hydrogen energy systems. A summary of the methodology is depicted in Figure 2.

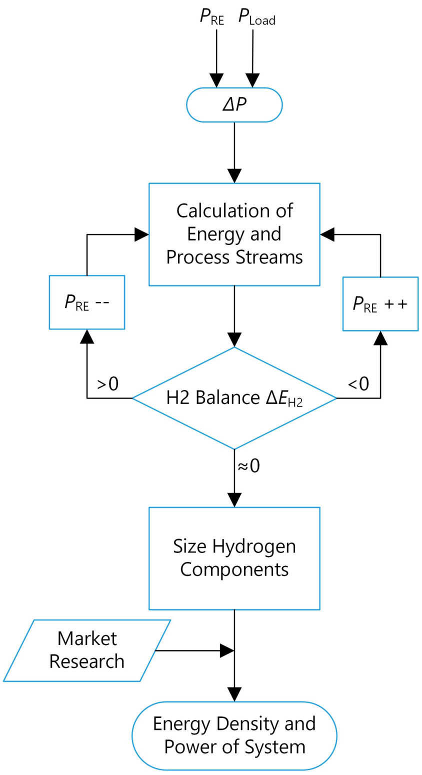


Figure 2 Methodology for estimating energy density and power of hydrogen energy systems.

The daily electrical energy demand from villages in Myanmar (Pandyaswargo et al., 2020), Kenya (Hansen and Xydis, 2018), Peru (Rinaldi et al., 2020) and Greece (Thomas et al., 2016) as shown in Table 3 are used as input for the electrical load P_{Load}.

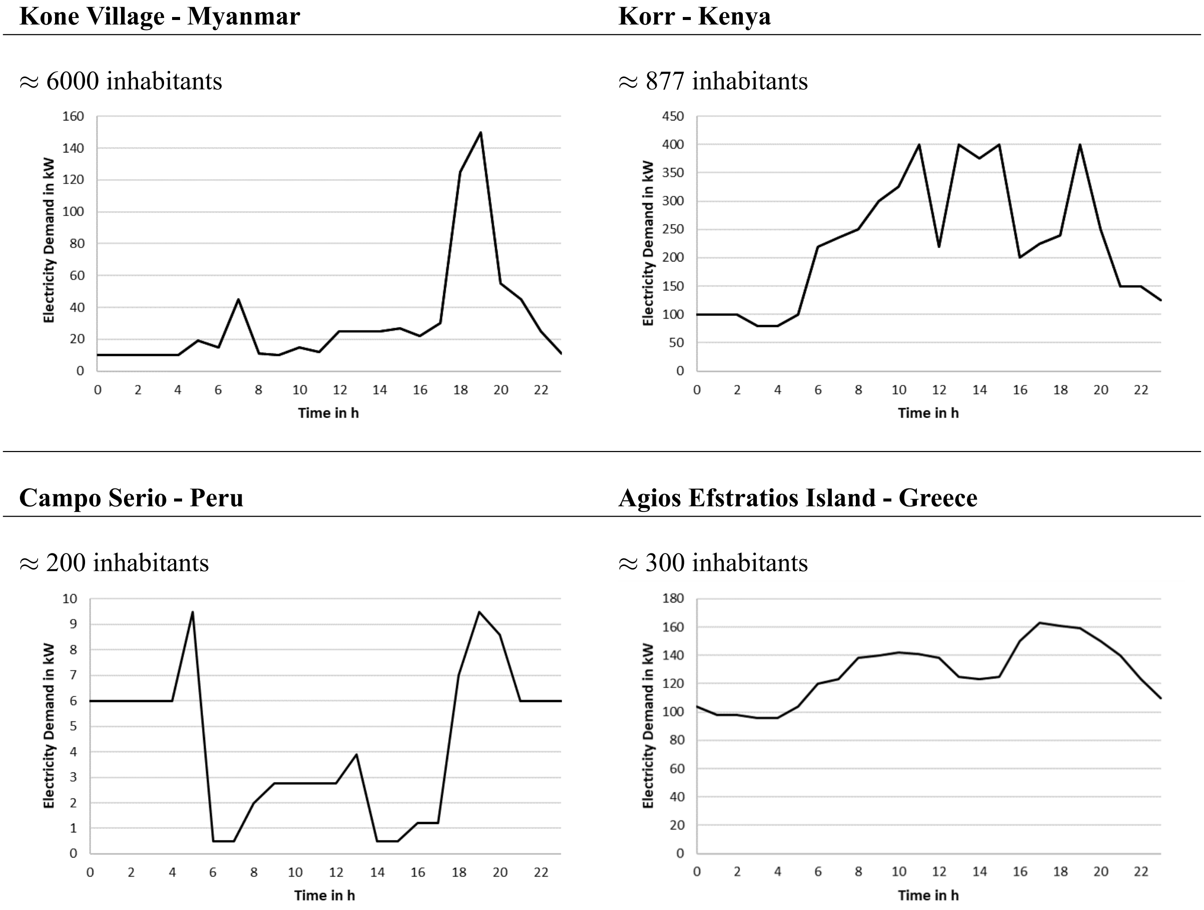
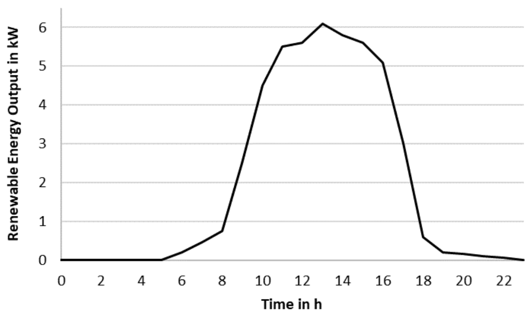


Figure 3 Overview of daily electricity demand in kW over 24 hours for considered off-grid locations.

RESULTS AND DISCUSSION

The power P_{RE} of renewable energy is described by the generic PV profile (Jing et al., 2015) as shown in Figure 4, which considers the efficiencies $\eta_{\text{H2}Gen} = 0.6$ and $\eta_{\text{H2}Re} = 0.55$, the resulting process and energy streams are summarized in Table 2. Moreover, the minimum power $P_{\text{H2}Gen_{min}} = 0.1$ for hydrogen generation is considered in the model assuming a state-of-the art PEM hydrogen generator with pressurized hydrogen output of 30 bar absolute pressure (Carmo et al., 2013). As a result, an additional compressor in the system is not necessary due to the absolute storage pressure of $p_{\text{H2}Store} = 30$ bar.



$\eta_{\text{H2}Gen} = 0.6$

$\eta_{\text{H2}Re} = 0.55$

$p_{\text{H2}Store} = 30$ bar

$T_{\text{H2}Store} = 20$ °C

$P_{\text{H2}Gen_{min}} = 0.1$

Figure 4 Generic renewable power output (Jing et al., 2015) for photovolatic power supply and parameters for hydrogen component sizing.

Table 2 Summary of hydrogen component sizing results for designated locations.

	Unit	Kone Village Myanmar	Korr Kenya	Campo Serio Peru	Agios Efstratios Island Greece
Renewable Power	kW	225	1270	35	805
H2 Generation	kW	200	945	32	680
H2 Storage	m^3	10.5	45.4	1.7	33
H2 Reconversion	kW	143	358	10	133

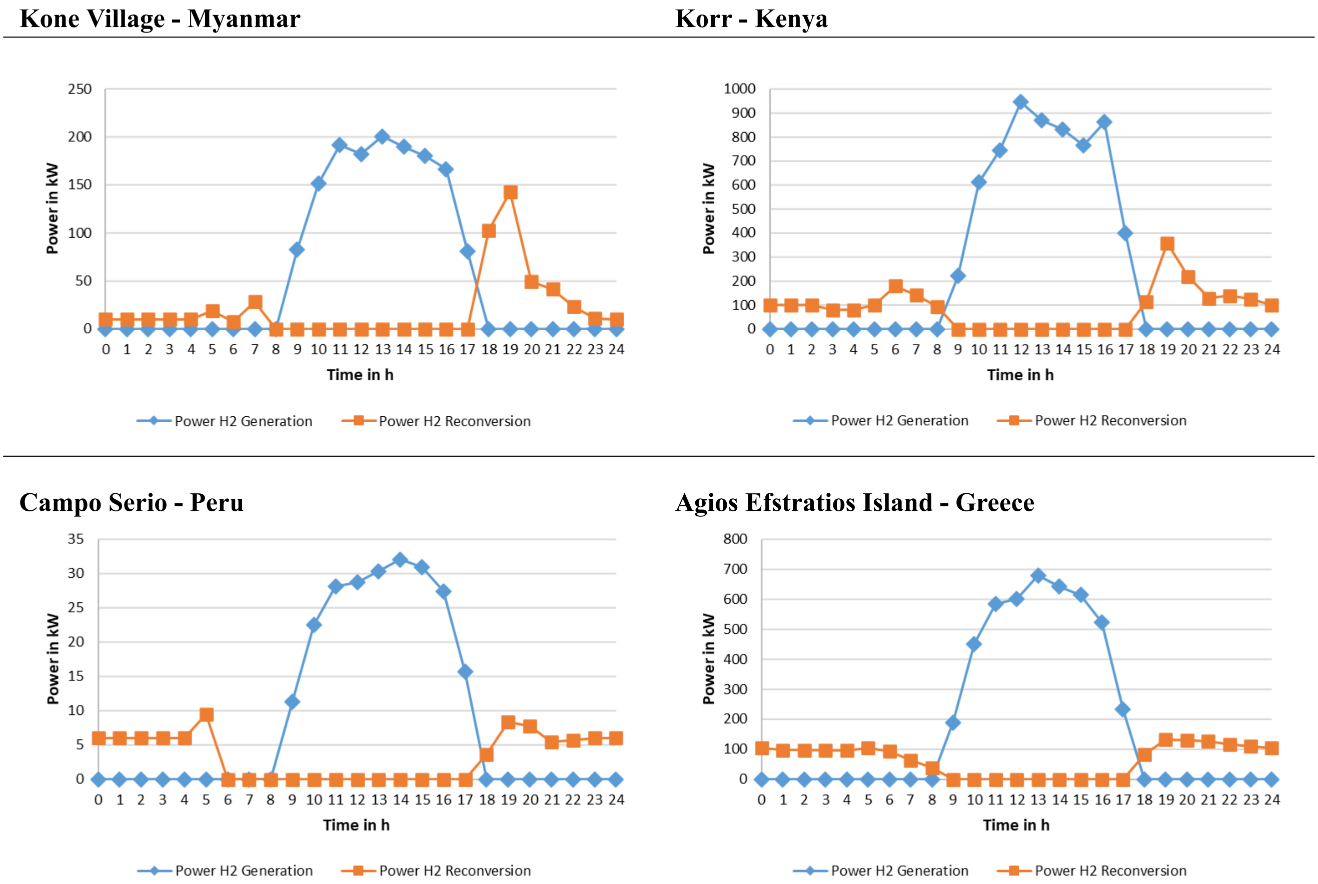


Figure 5 Overview of daily power in kW over 24 hours for hydrogen generation and hydrogen reconversion.

The different load curves (see Figure 3) lead to specific hydrogen generation and hydrogen reconversion profiles over 24 hours as visualized in Figure 5. The main time period for hydrogen generation is between 8 and 18 h for all four locations due to the use of the generic PV profile from Figure 4. If other renewable energy sources such as wind or hydro power are utilized, the times of availability of renewable power P_{RE} as well as the hydrogen generation and reconversion profiles will show different trends. During absence or insufficient renewable power, the load P_{Load} is covered by hydrogen reconversion.

The ratio between the area below the graph of hydrogen reconversion and generation describes the efficiency of the energy storage process. Since the efficiency of hydrogen generation and reconversion is assumed to be constant, it can also be calculated by:

$$\eta_{Overall} = \eta_{\mathrm{H2}Gen} \cdot \eta_{\mathrm{H2}Re} \tag{9}$$

In the analyzed case $\eta_{Overall} = 0.33$ meaning for 1 kWh of hydrogen reconversion energy approximately 3 kWh of hydrogen generation energy is needed. Comparing this to diesel generators and including the efficiency for conversion from crude oil to diesel, an overall efficiency from 0.14 to 0.27 for a diesel-based energy systems can be estimated. The efficiency range for the diesel energy system can be explained by a high dependency on the operating load. While consumption of diesel for one kWh of reconversion energy at minimal load ($\approx 20\% \, P_{rated}$) is 0.64 liters, it halves at higher loads of around 80% of the rated power (Staiger and Tanţău, 2020; Yamegueu et al., 2011). In hydrogen energy systems with PEM fuel cells, the efficiency of energy reconversion varies typically from 0.25 to 0.50 (Pandian et al., 2010). Moreover, hydrogen is produced and used on site in a hydrogen energy system, whereas diesel supply is dependent on external supply chains leading to additional transportation costs. All in all, hydrogen energy systems represent a climate-friendly alternative to conventional diesel generators, which are noisy, maintenance intensive, expensive and environmentally damaging (de Almeida et al., 2019). In order to discuss the relevance of containerized off-grid hydrogen energy systems, crucial design parameters such as energy density and power as well as the total volume and mass of the system need to be assessed. For this reason, commercially available hydrogen components for hydrogen generation, storage and reconversion have been investigated. It must be mentioned that the calculation does not take any equipment for renewable power generation or auxiliary equipment such as converters or controllers into account and focuses only on the units for hydrogen generation, storage and reconversion.

For the remote Kone Village in Myanmar, the most compact configuration measures 17 m^3 at a mass of approximately 9 tons. The rated hydrogen generation is calculated to be 204 kW and the hydrogen reconversion adds up to 153 kW with a hydrogen storage volume of 11 m^3 (see Table 3). Considering one standardized 20 ft container (L=6.058 m, H=2.591 m, W=2.438 m) according to ISO 668:2013-08, the components for hydrogen generation, storage and reconversion can be installed inside the container. However, auxiliary equipment and especially rectifiers for the numerous hydrogen generation units increase the actual size of the system and possibly exceed the weight or size limits. Alternatively, a 40 ft container (L=12.192 m, H=2.591 m, W=2.438 m) can be used to mount all components for the hydrogen energy system inside, but in both cases a more detailed elaboration of space requirements for the specific case needs to be performed.

For the island of Agios Efstratios in Greece, and Korr in Kenya, larger components are required and the volume and mass increase accordingly. The detailed results are summarized in Table 3 and indicate that an integrated single containerized solution for Agios Efstratios and Korr is technically not feasible due to the excess of the payload for a standardized 40 ft container (L=12.192 m, H=2.591 m, W=2.438 m) according to ISO 668:2013-08. For the remote village of Campo Serio in Peru it can be concluded that the minimum volume necessary to install all three hydrogen components is estimated to be 3 m^3 at a mass of approximately 1 ton proving feasibility of a containerized solution for Campo Serio with regards to mass and volume limitations. The rated hydrogen generation power in that case is 36 kW with 9 units and the hydrogen reconversion power 11 kW in one unit. The effective hydrogen storage energy considering the loss of energy due to reconversion by the fuel cell results to 77 kWh at a volume of 1.7 m^3 for the given storage pressure.

Table 3 Summary of results for the designated locations with regards to size, mass and rated power.

	Unit	Kone Village Myanmar	Korr Kenya	Agios Efstratios Island Greece	Campo Serio Peru
Total Volume	m^3	17	73	53	3
Total Mass	t	9	38	27	1
H2 Generation	kW	204	948	684	36
Units	-	51	237	171	9
Eff. H2 Storage	kWh	477	2068	1495	77
H2 Storage Volume	m^3	11	46	33	1.7
H2 Reconversion	kW	153	408	153	11
Units	-	3	8	3	1

In all four scenarios, the hydrogen storage is by far the largest fraction on the overall volume of the system. Regardless of the energy demand and size of the system, hydrogen storage is the main challenge for advancing hydrogen energy systems and, in particular, main improvement parameter for compact containerized solutions. As a result of this, the analyzed hydrogen energy systems for remote locations can be considered for low power output and small energy storage capacities as is the case for Campo Serio or even for higher energy demands as in Kone Village, where a single containerized hydrogen energy system as shown in Figure 1 reaches its limits. In order to enlarge the reach of hydrogen energy systems, effective methods for hydrogen storage need to be developed and further investigated. One way to increase the energy density is by compressing hydrogen. Storing hydrogen at 100 bar absolute pressure and a temperature of 20° C triples the effective hydrogen storage energy and for even larger pressures of 200 bar, 280 $\frac{kWh}{m^3}$ are possible provided $\eta_{H2Re} = 0.55$ (Linstrom, 1997) as can be seen in Figure 6. However, integrating an additional compressor in a containerized system poses new challenges and the trade-off between storage pressure, size of compression and cost need to be elaborated. Also, the increase in energy for compression and its availability influence the configuration of the system and the renewable power demand. There are numerous methods of storing hydrogen such as cryogenic, via cryo-adsorption, in metal hydrides or organic hydrides each with different storage conditions and performances (Veziroğlu, 2004; Niaz et al., 2015). For optimizing the storage density within a containerized hydrogen energy system, simple compact and reliable systems are needed so that compressed hydrogen is the favored option.

In Figure 6, the power of hydrogen generation and reconversion as well as the effective energy storage density for Campo Serio and Kone Village are visualized. As an example to demonstrate the relevance of hydrogen compression in the system, the effective storage energy for Kone Village is increased by compressing hydrogen to an absolute pressure of 200 bar. Consequently, the effective energy storage density rises from $\approx 45 \frac{kWh}{m^3}$ to $\approx 280 \frac{kWh}{m^3}$ enabling the stored energy of

Kone Village to fit in the storage volume of 1.7 m^3 of Campo Serio and thereby decreasing the hydrogen storage volume by 9.3 m^3. It needs to be noted that due to the pressure increase, the wall thickness of the tanks and therefore the overall size of the storage system gain in size. The feasible area of application based on the analysis of the four off-grid locations and the potential area of application, which expands with increasing energy storage density, are marked in Figure 6.

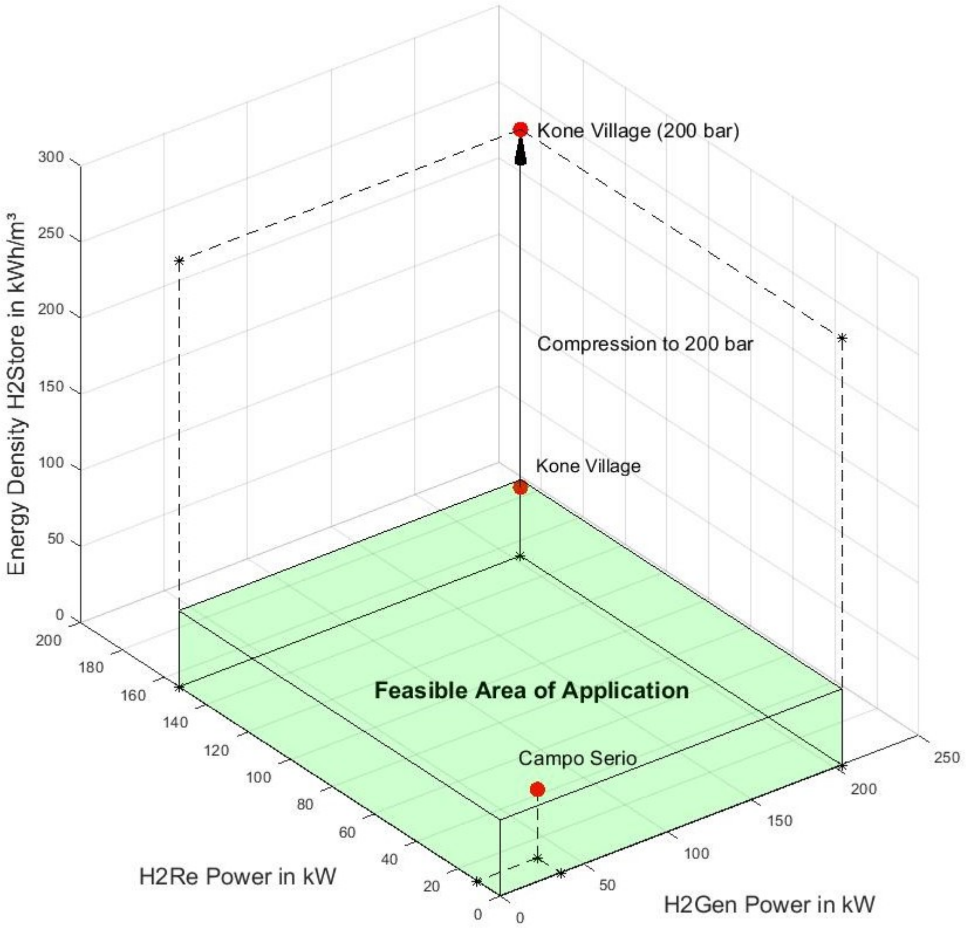


Figure 6 Range of application for single containerized self-sufficient hydrogen energy systems based on the results of Campo Serio and Kone Village.

CONCLUSIONS

This work shows that self-sufficient hydrogen energy systems are a relevant option for clean energy supply in off-grid locations and need to be considered for electrification of rural areas. In particular, containerized solutions with easy installation and compact design offer opportunities for small villages as Campo Serio in Peru to have secure and independent energy supply. Moreover, containerized hydrogen energy systems are able to cover the energy demand of larger villages such as Kone Village in Myanmar. By further optimizing the system with regards to hydrogen storage technologies and reachable energy densities as well as efficiencies of hydrogen generation and reconversion, self-sufficient hydrogen energy systems can become an established way of energy supply for remote regions. The next steps in reaching this goal include a detailed assessment of limits for containerized solutions and the development of a compact and modular system based on state-of-the-art technologies in order to widen the range of application for self-sufficient hydrogen energy systems. As a final step the economic viability needs to be analyzed and potential sites for installation of the system shall be identified.

NOMENCLATURE

AEL	Alkaline electrolysis
AEMEL	Anion exchange membrane electrolysis
ΔE_{H2}	Hydrogen balance
FCHJU	The Fuel Cells and Hydrogen Joint Undertaking
H	Height
L	Length
LHV_{H2}	Lower heating value of hydrogen
m_{H2}	Mass of stored hydrogen
PEMEL	Proton exchange membrane electrolysis
PEMFC	Proton exchange membrane fuel cell
p_{H2Store}	Storage pressure
ΔP	Power difference
$P_{\mathrm{H2}Gen}$	Power for hydrogen generation
$P_{\mathrm{H2}Gen_{min}}$	Minimum power for hydrogen generation
$P_{\mathrm{H2}Re}$	Power from hydrogen reconversion
P_{Load}	Electrical load
P_{RE}	Power from renewable energy
$P_{\mathrm{RE,Load}}$	Power for direct load coverage
$\dot{Q}_{\mathrm{H2}Gen}$	Heat from hydrogen generation
$\dot{Q}_{\mathrm{H2}Re}$	Heat from hydrogen reconversion
R_{H2}	Hydrogen gas constant
Δt	Time interval
T_{H2Store}	Storage temperature
$\dot{V}_{\mathrm{H2}Gen}$	Hydrogen generation
$\dot{V}_{\mathrm{H2}Store}$	Hydrogen reconversion
$\dot{V}_{\mathrm{O2}}$	Oxygen generation
$\dot{V}_{\mathrm{W}}$	Water consumption
V_{H2Store}	Storage volume
W	Width
η_{H2Gen}	Hydrogen generation efficiency
η_{H2Re}	Hydrogen reconversion efficiency

References

Akikur, R., Saidur, R., Ping, H. and Ullah, K. (2013), 'Comparative study of stand-alone and hybrid solar energy systems suitable for off-grid rural electrification: A review', *Renewable and Sustainable Energy Reviews* **27**, 738–752.

Akinyele, D., Olabode, E. and Amole, A. (2020), 'Review of fuel cell technologies and applications for sustainable micro-grid systems', *Inventions* **5**(3), 42.

Ayers, K., Danilovic, N., Ouimet, R., Carmo, M., Pivovar, B. and Bornstein, M. (2019), 'Perspectives on low-temperature electrolysis and potential for renewable hydrogen at scale', *Annual Review of Chemical and Biomolecular Engineering* **10**(1), 219–239.

Bhandari, B., Lee, K.-T., Lee, C. S., Song, C.-K., Maskey, R. K. and Ahn, S.-H. (2014), 'A novel off-grid hybrid power system comprised of solar photovoltaic, wind, and hydro energy sources', *Applied Energy* **133**, 236–242.

Carmo, M., Fritz, D. L., Mergel, J. and Stolten, D. (2013), 'A comprehensive review on PEM water electrolysis', *International Journal of Hydrogen Energy* **38**(12), 4901–4934.

de Almeida, A., Moura, P. and Quaresma, N. (2019), 'Energy-efficient off-grid systems—review', *Energy Efficiency* **13**(2), 349–376.

Fathima, A. H. and Palanisamy, K. (2015), 'Optimization in microgrids with hybrid energy systems – a review', *Renewable and Sustainable Energy Reviews* **45**, 431–446.

Federal Ministry for Economic Affairs and Energy (BMWi) (2020), 'The national hydrogen strategy'. accessed 18.03.2021. **URL:** *https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.html*

Gstöhl, U. and Pfenninger, S. (2020), ‘Energy self-sufficient households with photovoltaics and electric vehicles are feasible in temperate climate’, *PLOS ONE* **15**(3), e0227368.

Hansen, J. M. and Xydis, G. A. (2018), ‘Rural electrification in kenya: a useful case for remote areas in sub-saharan africa’, *Energy Efficiency* **13**(2), 257–272.

IRENA (2020), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal*, International Renewable Energy Agency, Abu Dhabi. accessed 18.03.2021.
URL: *https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction*

Jing, W., Wong, M. D., Lai, C. H. and Wong, W. S. H. (2015), Smart hybrid energy storage for stand-alone PV microgrid: Optimization of battery lifespan through dynamic power allocation, *in* ‘2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)’, IEEE.

Kavlak, G., McNerney, J. and Trancik, J. E. (2018), ‘Evaluating the causes of cost reduction in photovoltaic modules’, *Energy Policy* **123**, 700–710.

Kurzweil, P. (2016), *Brennstoffzellentechnik*, Springer Fachmedien Wiesbaden.

Lamb, J. J., Burheim, O. S. and Pollet, B. G. (2020), Hydrogen fuel cells and water electrolysers, *in* ‘Micro-Optics and Energy’, Springer International Publishing, pp. 61–71.

Ligen, Y., Vrubel, H. and Girault, H. (2020), ‘Energy efficient hydrogen drying and purification for fuel cell vehicles’, *International Journal of Hydrogen Energy* **45**(18), 10639–10647.

Linstrom, P. (1997), ‘Nist chemistry webbook, nist standard reference database 69’.

Lymperopoulos, N., Tsimis, D., Aguilo-Rullan, A., Atanasiu, M., Zafeiratou, E. and Dirmiki, D. (2019), ‘The status of SOFC and SOEC r&d in the european fuel cell and hydrogen joint undertaking programme’, *ECS Transactions* **91**(1), 9–26.
URL: *https://doi.org/10.1149/09101.0009ecst*

Niaz, S., Manzoor, T. and Pandith, A. H. (2015), ‘Hydrogen storage: Materials, methods and perspectives’, *Renewable and Sustainable Energy Reviews* **50**, 457–469.

Pandian, M. S., Anwari, M., Husodo, B. Y. and Hiendro, A. (2010), Efficiency and economics analysis of proton exchange membrane fuel cell, *in* ‘2010 Conference Proceedings IPEC’, IEEE.

Pandyaswargo, A. H., Ruan, M., Htwe, E., Hiratsuka, M., Wibowo, A. D., Nagai, Y. and Onoda, H. (2020), ‘Estimating the energy demand and growth in off-grid villages: Case studies from myanmar, indonesia, and laos’, *Energies* **13**(20), 5313.

Puranen, P., Kosonen, A. and Ahola, J. (2021), ‘Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates’, *Solar Energy* **213**, 246–259.

Rinaldi, F., Moghaddampoor, F., Najafi, B. and Marchesi, R. (2020), ‘Economic feasibility analysis and optimization of hybrid renewable energy systems for rural electrification in peru’, *Clean Technologies and Environmental Policy* .

Ritchie, H. and Roser, M. (2019), ‘Access to energy’, *Our World in Data* . https://ourworldindata.org/energy-access.

Santangelo, P. E. and Tartarini, P. (2018), ‘Effects of load variation and purge cycles on the efficiency of polymer electrolyte membrane fuel cells for stationary applications’, *Journal of Renewable and Sustainable Energy* **10**(1), 014301.

Sdanghi, G., Maranzana, G., Celzard, A. and Fierro, V. (2019), ‘Review of the current technologies and performances of hydrogen compression for stationary and automotive applications’, *Renewable and Sustainable Energy Reviews* **102**, 150–170.

Shi, X., Liao, X. and Li, Y. (2020), ‘Quantification of fresh water consumption and scarcity footprints of hydrogen from water electrolysis: A methodology framework’, *Renewable Energy* **154**, 786–796.

Staiger, R. and Tanțău, A. (2020), *Geschäftsmodellkonzepte mit grünem Wasserstoff*, Springer Fachmedien Wiesbaden.

Thomas, D., Deblecker, O. and Ioakimidis, C. S. (2016), ‘Optimal design and techno-economic analysis of an autonomous small isolated microgrid aiming at high RES penetration’, *Energy* **116**, 364–379.

Tong, W., Forster, M., Dionigi, F., Dresp, S., Erami, R. S., Strasser, P., Cowan, A. J. and Farràs, P. (2020), ‘Electrolysis of low-grade and saline surface water’, *Nature Energy* **5**(5), 367–377.

Ursua, A., Gandia, L. M. and Sanchis, P. (2012), 'Hydrogen production from water electrolysis: Current status and future trends', *Proceedings of the IEEE* **100**(2), 410–426.

Veziroğlu, T. (2004), *Hydrogen materials science and chemistry of carbon nanomaterials*, Kluwer Academic, Dordrecht Boston London.

Vincent, I. and Bessarabov, D. (2018), 'Low cost hydrogen production by anion exchange membrane electrolysis: A review', *Renewable and Sustainable Energy Reviews* **81**, 1690–1704.

von Böckh, P. and Stripf, M. (2015), *Technische Thermodynamik*, Springer Berlin Heidelberg.

Wulf, C., Linssen, J. and Zapp, P. (2018), Power-to-gas—concepts, demonstration, and prospects, *in* 'Hydrogen Supply Chains', Elsevier, pp. 309–345.

Yamegueu, D., Azoumah, Y. and Py, X. (2011), Experimental and economical study of sustainable electricity generation by solar PV/diesel hybrid systems without storage for off grid areas, *in* 'Energy and Sustainability III', WIT Press.

Zhang, L. (2020), *Electrochemical water electrolysis : fundamentals and technologies*, CRC Press, Taylor & Francis Group, Boca Raton.

Züttel, A. (2003), 'Materials for hydrogen storage', *Materials Today* **6**(9), 24–33.

APPENDIX A

Table 4 Size and mass of commercially available single units for hydrogen generation, storage and reconversion applied in sizing calculation for examined off-grid locations.

Location	Component	Length in mm	Width in mm	Height in mm	Mass in kg
Kone Village	H2Gen	485	405	580	50
	H2Store	840	840	1870	215
	H2Re	408	406	261	47
Korr	H2Gen	485	405	580	50
	H2Store	540	540	2396	191
	H2Re	973	406	261	110
Campo Serio	H2Gen	485	405	580	50
	H2Store	840	840	1870	215
	H2Re	408	406	261	47
Agios Efstratios	H2Gen	485	405	580	50
	H2Store	540	540	2396	191
	H2Re	973	406	261	110