Demonstrator Mariestad
WP4 RISE Report

ACES project
Adaptive Control of Energy Storage

Final Version

RISE

2021-02-01

INTERNAL REFERENCE:

Deliverable name	Work package 4 RISE report
Author(s):	Ellinor Forsström (RISE) Anders Lundblad (RISE) Axel Nordin Fürdös (RISE)
Reviewer(s):	Ivan Löfgren (WSP) Christian Sundvall (Insplorion)
Released by:	Ellinor Forsström (RISE)
Lead Partner:	Metrum Sweden AB
Document (File):	ACES_WP4_RISE_sub_report_final
Issue (Save) date:	2021-02-01
Confidentiality (TLP):	**COLOR - WHITE**

DOCUMENT SENSITIVITY

☒	**Not Sensitive**	Contains only factual or background information; contains no new or additional analysis, recommendations or policy-relevant statements
☐	**Moderately Sensitive**	Contains some analysis or interpretation of results; contains no recommendations or policy-relevant statements
☐	**Sensitive**	Contains analysis or interpretation of results with policy-relevance and/or recommendations or policy-relevant statements
☐	**Highly Sensitive Confidential**	Contains significant analysis or interpretation of results with major policy-relevance or implications, contains extensive recommendations or policy-relevant statements, and/or contain policy-prescriptive statements. This sensitivity requires SB decision.

VERSION MANAGEMENT

Version	Status	Date	Changes
1.1		2020-12-03	-
2.0		2020-12-17	Changes according to feedback from project partners
2.1 (Final)	Released	2021-02-01	Released by WP4 RISE Lead

TRAFFIC LIGHT PROTOCOL (TLP)[1]

The Traffic Light Protocol (TLP) was created by the UK Centre for the Protection of National Infrastructure (CPNI) in order to encourage greater sharing of information. In order to encourage the sharing of sensitive (but unclassified) information, however, the originator needs to signal how widely they want their information to be circulated beyond the immediate recipient, if at all. The TLP is based on the concept of the originator labelling information with one of four colours to indicate what further dissemination, if any, can be undertaken by the recipient. The recipient must consult the originator if wider dissemination is required.

Sharing of information is classified with four states (colours). The four colours and their meanings are:

RED — **Personal distribution for named recipients only**

Information is shared in the context of a meeting, for example. RED information is limited to those present at the meeting. In most circumstances, RED information will be passed verbally or in person.

YELLOW — **Limited distribution**

The recipient may share YELLOW information with others within their organisation, but only on a 'need-to-know' basis. The originator may be expected to specify the intended limits of that sharing.

GREEN — **Community wide distribution**

Information in this category can be circulated widely within a particular community. However, the information may not be published or posted on the Internet, nor released outside of the community.

WHITE — **Unlimited distribution**

Subject to standard copyright rules, WHITE information may be distributed freely, without restriction.

[1] RULES OF PROCEDURE FOR THE EUROPEAN FORUM FOR MEMBER STATES (EFMS) ON PUBLIC POLICIES FOR SECURITY AND RESILIENCE IN THE CONTEXT OF CRITICAL INFORMATION INFRASTRUCTURE PROTECTION, Version 3.0 FINAL – May 2011 "Traffic Light system"

ABSTRACT

Introduction

In this report the work and result from test-site Mariestad will be presented. The report covers a description of the system, a summary of the work process as well as lessons learned from the demo-site. Furthermore, the report includes a brief outlook on potential additional business opportunities for hydrogen storage units and a theoretical economic analysis based on the demonstrator.

Background

The demonstrator site in focus for this report consist of a hydrogen refuelling station (HRS) which, combine solar powered H_2-production (hydrogen production), H_2-storage and a battery storage. The system is unique in its set-up and constitutes an important milestone in the city of Mariestad's future energy strategy. However, during the course of the project several hindrances appeared, mostly connected to the operational permit, which, lead to severe delays in the work-plan. Not until the summer of 2020 the system could be taken in operation, and still then, just partly. This prevented the collection of any relevant operational data from the demonstrator within the time-frame of this project.

Results and conclusions

Although the delays in the launching prevent any real data to be obtained some important lessons could be drawn from this project which, could significantly streamline a future installation of this kind. The most important conclusions that are presented in the report can be summarized by;

1. In order to enable a large scale and efficient roll-out of hydrogen-based systems there is a need to enhance concerned authorities (i.e. Swedish Civil Contingencies Agency) knowledge of the technology, in particular safety aspects.
2. Stricter requirements towards the manufacturer are needed regarding the certification of HRS units. This in order to avoid any future uncertainties regarding the safety aspects of the technology.
3. Today, the fixed cost outweighs the non-fixed cost of a commercial HRS but as technology continue to progress the cost of the installation decreases. At the same time the non-fixed cost may increase due to altered prerequisites on the energy market which, could tip the scale of this relation.

Managing Partner:

Partners:

Observers:

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Energy Systems' focus initiative Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646039.

TABLE OF CONTENTS

1. Acronyms

ACES	Adaptive Control of Energy Storage

2. Introduction

The Demonstrator Mariestad – WP 4 report is created as part of the Adaptive Control of Energy storage (ACES) project.

The Adaptive Control of Energy storage (ACES) project has been performed by a consortium of ten [10] partner organisations: lead partner Metrum Sweden AB (Sweden), Glava Energy Center (Sweden), RISE Research Institutes of Sweden AB (Sweden), Insplorion AB (Sweden), Rejlers Embriq A/S (Norway), MINcom Smart Solutions GmbH (Germany), Fraunhofer Institute for Factory Operation and Automation IFF (Germany), Krebs engineers GmbH (Germany), VänerEnergi AB (Sweden), ABB AB (Sweden).

The ACES project has received funding from the Swedish Energy Agency, The Research Council of Norway and the German Federal Ministry of Economic Affairs and Energy in the framework of the joint programming initiative ERA-Net Smart Grids Plus, with support from the European Union's Horizon 2020 research and innovation programme.

The overall objective of the ACES project is to develop, implement test advanced measurement technology and adaptive control algorithms for energy storage systems in order to allow for improved economics of operation. By reaching the project objectives, the ACES project aim to contribute to an affordable 100% renewable power system with smart battery storage solutions using artificial intelligence.

More information on the ACES project can be found on: http://www.acesproject.eu/

PURPOSE

The ACES project has been organized in six [6] different work packages with multiple dependencies and collaborations in-between. This purpose of this very report is to present the findings and conclusions related to project goals of work package 4. In addition, a general description and evaluation of the project execution is given, in order to share not only findings related to the project objectives, but also learnings about project methodology and tools in order to further contribute to the research community regarding successful project design.

GOALS AND RESEARCH QUESTIONS

The goals of work package 4 has been to

- **Establish 4 operational demonstrator sites, combining the outcomes of WP2, 3 and 5**
- **Test reports to prove conclusions**

This report shall describe the work and progress on one of the four demonstrator sites, namely the HRS unit in Mariestad.

3. Background information

The demonstrator site in focus for this report is placed in Mariestad, Sweden and is unique in its set-up. It consists of a hydrogen refuelling station (HRS) which, combine solar powered H2-production, H2-storage and a battery storage. The responsible parties and initiator for this system are the local energy company VänerEnergi together with the technology provider Nilsson Energy. The system has been installed and developed in multiple-step process, which, started with the launch of a hydrogen fuelling station. Next, the system was accompanied with solar power and an electrolyser to enable local hydrogen production. The goal of this site was to ensure that all the hydrogen used at the station and produced in Mariestad should be renewable and emission-free. In many aspects, the over-all objective of this work-package was to demonstrate and showcase a new hydrogen-based energy infrastructure that could be adapted to numerous applications. At this specific site mobility was targeted but the technology has a much broader application area, stretching from providing energy to real estates, businesses or industry-environments.

4. Methodology

DEMONSTRATORS

In figure 1 below the HRS system is described. As shown, all the solar energy produced at the site is utilised, either by being stored in hydrogen (trough electrolysis) or directly supplied as electricity to the grid. Hydrogen can also be transformed to electricity and heat via the fuel cell unit.

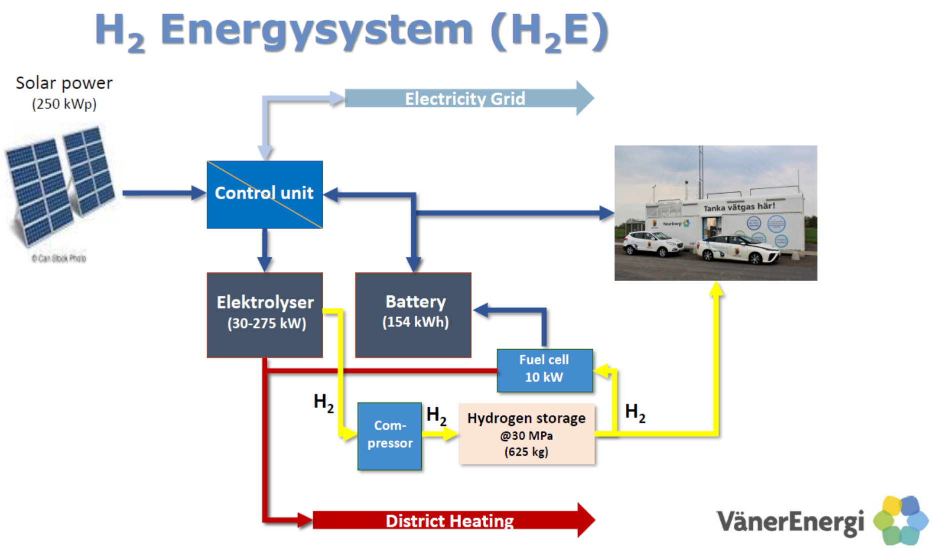

Figure 1: A schematic description of how the HRS-unit and energy storage system is configured.

In table 1 the operating scheme (strategy) throughout a year is described.

Table 1: Strategy for operating the system during different seasons

Day operation "Summer"	***Night operation "Summer"***	***Day operation "winter"***	***Night operation "winter"***
1. Solar energy is used to power electro-lyser, compressor and fuelling station. H2 storage is filled up.	1. Battery supplies the fuelling station with electricity.	1. The fuel cell is used as backup to supply the fuelling station with energy in case of low solar yield	1. Battery + fuel cell supplies the fuelling station with energy
2. Battery comple-ments solar energy when required.	2. Fuel cell is used as back-up in case the battery is emptied.	2. Stored hydrogen from the summer sea-son is used to supply the fuelling station	2. Stored hydrogen from the summer sea-son is used to supply the fuelling station
3. Battery is charged by solar power.			

In the next section all the included key-components which, has been installed at the Mar-iestad site will be described in further detail.

TECHNOLOGY

Battery

Manufacturer	TesVolt
Model	Samsung SDI cells
Capacity	154 kWh
Load cycles	8000
Characteristic	Short reactiontime

Fuelcell

Manufacturer	Powercell
Model	Powercell PS-5
Capacity	0,3 kg H2/ hour
Power output	5 kW (electricity), 5 kW (heat)
Characteristic	Short start-up time

Solar power plant

Power	250 kWp
No. PV panels	770
Year production	235 MWh
Solar productive area	1500 m
No. inverters	10
Avoided annual CO2 emission	144 ton
Spec. annual spec.ratio	941 kWh/kWp

Electrolyser

Power consumption stack	250 kW
Power consumption system	277 kW
Hydrogen production	60 Nm3 /h or 5.4 kg/h
Stack voltage	< 250 V
Stack current	< 1300 A
System pressure	35-40 bar
System temperature	100 C
Response time	< 1 second
Dynamic range	10-100%
Lifetime	Lifetime: >10 years
Footprint	1800x1100x2300mm
Weight	< 3500 kg

Compressor

Model	MKZ 400-5
Capacity	74 scfm (~125 Nm3/h)
Suction pressure	203 psi (14 bar)
Discharge pressure	450 psi (31 bar)

Hydrogen storage

No. units	2,5
Capacity	20 Mpa 500kg

DATA COLLECTION

Due to unexpected hindrance with the operation permit the system has not been in use according to the initial plan. Consequently, no data collection has been possible. If the work would have proceeded according to the initial plan, data would have been collected regarding the hydrogen production, grid feed-in, fuelling volumes and solar production in order to conduct and analyse a variety of business models. The reasons behind the lack of data are more thoroughly described in the section "lessons learned".

5. Result and discussion case Mariestad

LESSONS LEARNED

At the beginning of the project, the prospect of getting the HRS system installed and in function was viewed as fairly straightforward and without any substantial complications. The sub-project had received a lot of public attention and support and the first step of the project, installing the H_2-fuelling station (established in Jan 2017) progressed successfully. Furthermore, all the technical aspects regarding the expansion had been reviewed, analysed and ordered in advance. However, during the course of the project several hindrances appeared that in the end have delayed the launch to the extent that, at the present day, the system is just partially in use even though the whole system is installed.

The main reason for this can be explained by considerable delays in the permit process. More, specifically the permit regarding the safety aspects of the system which, is issued by the Swedish Civil Contingencies Agency. In January 2017 the H_2-fueling station was inaugurated and taken in operation. At this moment the installation only consisted of a fuelling station which, was supplied with externally delivered and purchased H_2. As described in the previous section, the continued plan to develop this site to a complete self-reliant HRS facility had already been considered and all the technical aspects of the undertaking had been prepared. But as the next step of the installation plan proceeded (i.e. enhancing the fuelling station to a full-scale HRS) it became clear that the approved permit would no longer be sufficient and cover the more advanced system. The problem that had arisen was the permit that originally had been granted was delimited to the system as one complete unit. As the system became more complex and consisted of unproven and state-of-the art technologies the Regional Fire and Rescue services (on behalf of the Swedish Civil Contingencies Agency) commissioned a risk analysis in which, each and every component of the system was analysed individually in order to give VänerEnergy permission to operate the system. To meet these demands a risk-consultant was hired to evaluate the now installed HRS system according to the new guidelines. The result become very comprehensive with a lot of observations on safety-aspects that needed to be addressed. Conclusively, this postponed the granting of the operating permit until the summer of 2020, and the HRS could finally start producing H_2. Since then a lot of technical adjustments have been made to modify the operation and there is still some work left before the HRS could work at full capacity.

At the day of writing, the HRS partly produce and partly purchases the H_2 needed to supply the system. This due to the fact that even though the system and all its components have been CE-certified, validated and approved for operation the permit contains a condition which, states that the H_2 transfer between the electrolyser to the H_2 storage has to be supervised by an appointed responsible part. In practice, this implies that an appointed person from VänerEnergy must be at the site when the transfer of H_2 takes place. This, of course, gets impossible to uphold which, has resulted in that purchased H_2 is used to supply the fuelling station throughout the weekends. At present, VänerEnergy is working on a solution to this by developing a digital surveillance system which, would meet the requirements stated in the permit.

Furthermore, the feed into the district heating grid has not been established. The reason for this is that the waste heat from the electrolysis at this point doesn't hold sufficiently high enough temperature to contribute to the grid.

In summary, a number of lessons can be drawn:

- As stated, a major setback for the demo-site is the fact that the permit process become much more protracted than expected. Partly, due to that the risk analysis became considerably more extensive and thorough than VänerEnergy anticipated.

But mainly, it can be explained by a lack of knowledge of hydrogen based technologies at the concerned authorities. As the involved technologies together constitutes a novel concept, there is a shortage of comprehensive regulations and guidelines on how to install and operate the system, leading to excessive safety precautions.

- One conclusion made by VänerEnergy is that in a potential future scenario with a similar set-up, they will impose stricter requirements towards the manufacturer regarding their insurance that the entire system would be certified as one unit. That would have spared VänerEnergy the work of providing an internal risk analysis for each component in this specific setting. In such a case they would only need to make an exterior risk analysis and not at the component level.
- As a consequence of the elaborate risk analysis, several additional safety measures were needed in order to comply with the demands from the Regional Fire and Rescue services. To reduce the need of these additional safety measures, some components would gain from being installed separately instead as one combined unit (if not the unit would be pre-certified as stated in the previous section). E.g. separate the H_2-storage, electrolyser and the control unit from each other.
- In order to approach additional H_2-markets and needs, VänerEnergy has already made plans for expanding the unit so that it enables H2 to be bottled and offered to industrial customers.
- In the future, the HRS could also be used to store the oxygen that is created during the electrolysis to further expand the business case of the system.

FUTURE PLANS IN MARIESTAD

Due to the delay a new and altered time-frame was drawn according to which VänerEnergy aims at operating the system at full capacity by the summer of 2021. Although the project has been severely delayed, Vänerenergy have already made plans of how to further expand the unit. Two overall objectives;

- Increase the use of surplus energy from renewable energy production through electrolysis and hydrogen production.
- Increasing the capacity of the existing system by increasing the installed solar power and expanding the storage capacity

To meet these ambitions two alternative action plans are being considered.

Option 1 *Connect additional renewable energy sources:*

- Collaboration with Rabbalshedekraft (local wind-power provider)
- Increase the efficiency of usage of the electrolyser and grid connection.
- Prepare the unit to be able to react swiftly to increased hydrogen sales. Mainly by enabling bottling of produced hydrogen but also create long-term contract with hydrogen dependent industry-clients.

Option 2 *Increase the installed power of the solar energy:*

- Increased degree of self-sufficiency to the degree of 100% solar produced hydrogen
- Gradually expand electrolyser capacity
- Increase the power output to the grid

In table 2 a summary of the economical profitability of an expansion of the system's capacity is presented. At present the system has a capacity to accommodate 20 vehicles. The calculations are based on the cost of hydrogen being fixed at 100 SEK/kg.

Table 2: Projected profitability of a potential expansion of the HRS in Mariestad

Profitability of the HRS in Mariestad			
Business-case	30 fuel cell vehicles	100 fuel cell vehicles	100 fuel cell vehicles
Payback period (years)	15	13	10
ROI (%)	1,6	3,9	7,3

OUTLOOK ON POTENTIAL ADDITIONAL BUSINESS OPPORTUNITIES FOR HYDRIGEN STORAGE

Grid Support

As described in the set up for the HRS in Mariestad, one possible service the system can provide is grid support. This, however, can be done at different scale and offer different services to the grid. In contrast to the case in Mariestad, which, constitutes a rather small-scale system, a larger electrolysis unit could provide more advanced services to the grid beyond demand response and load control. Some examples include ancillary services to grid operators by supplying Frequency Control and ramping services. Just like in the case of the small-scale system, the surplus hydrogen can be delivered to multiple markets or uses (see Alternative hydrogen markets).

Integration of large-scale renewables

As the integration of renewables in the energy mix is increasing, the need for reliable energy production follows. In order to accommodate this, it is vital to be able to store energy. In comparison to a generic battery storage, a hydrogen storage could provide additional value, as it paves way to seasonal storage and it could improve the business case for the renewables as it opens new market pathways. As both renewables and hydrogen technologies have economic benefits regarding the amplitude of the installation, this would be suitable for large scale renewables sites.

Re-conversion to grid electricity

One additional way to gain value from a hydrogen storage is to convert hydrogen back to grid electricity. This however, is not often seen as one of the services with the highest potential due to the significant energy losses the multiple conversation-steps causes. Although this may prove viable for remote locations that require longer-term and seasonal storage. In those cases where it is feasible, it can be achieved by using either stationary fuel cells or thermal conversion units. The oxygen by-product of electrolysis can be used to improve either combustion or fuel cell re-conversion efficiency.

A buffer level in the H_2storage (which, never is emptied) in combination with a fuel cell could provide more long term emergency power (e.g. for several days.)

Alternative hydrogen markets

In addition to the value gained from several grid services the biggest advantage of an electrolyser and storage system compared to a battery storage is of course that the produced hydrogen opens up the pathway to additional markets. The hydrogen can be used, just like the case in Mariestad, to support transport needs by feeding a fuelling station to light weight vehicles. But it can also be used to fuel heavy vehicles such as buses and material handling equipment (forklifts, tugs etc). In addition it can be stored and bottled to reach several hydrogen dependent industries (which, is the future plan in Mariestad).

6. Economic review – Commercial HRS

As the delays surrounding the HRS case in Mariestad prevented the collection of operational data, it was impossible to perform an economic analysis of this specific demonstrator. In order to compensate for this and still gain some insight regarding the business case associated with a commercial HRS a model of a similar set-up as the one in Mariestad was simulated and analysed.

DISCLAIMER: This case is based upon the HRS in Mariestad. However, it is not identical in all aspects and it contains differences in both design and connected services.

SYSTEM DESIGN

Like the case in Mariestad, the system in focus for this analysis has connected solar panels as well as a grid connection. The HRS is intended to serve private customers in FCEV cars. The main idea is that during the summer the HRS will be solar powered while in the winter it will rely more on grid power and seasonally stored hydrogen (produced during summer). In figure 2 the system design is shown. The installed solar power is set to 250kWp, as this allows the HRS to count as a "microproducer" by Swedish law. The HRS can sell excess electricity at the Nordpool spot-price as long as it sells less electricity than it consumes, for every kilowatt-hour sold that exceeds its own consumption there will be a fee of 0.20 SEK/kWh applied at the end of the year.

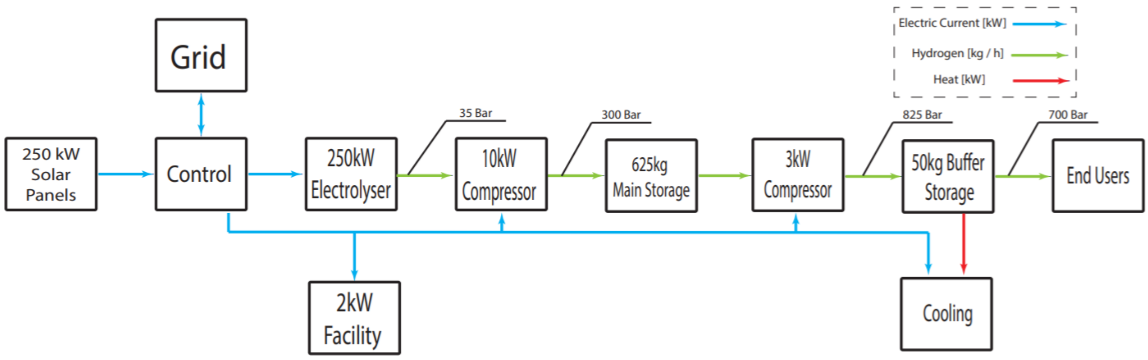

Figure 2: Commercial HRS - System Design

COST COMPARISON

In the economic analysis three different set-ups were compared. The default design, an improved version of the default design, with 100kg main storage and a 13.8kW / 14.4kWh battery and finally a non-solar design with 100kg main storage and 0 kWp solar panels (all else being the same as the default)

Fixed Costs

The fixed costs for the different set-ups are presented in table 3 These are the costs that the HRS will present regardless of external factors such as user demand and solar power. What is not shown in the table but included in the calculations is that at the 10 year mark the electrolyser has to be replaced at a cost of 1650 k SEK (same for all set-ups).

Table 3: Investment and O & M. (Investment includes capex and installation)

	Default Design		Improved Design		No Solar Design	
Costs [k SEK]	Investment	O & M	Investment	O & M	Investment	O & M
Solar Panels	250	-	250	-	-	-
Electrolyses	290.5	132	290.5	132	290.5	132
Compressor(s)	533.58	60.26	533.58	60.26	533.58	60.26
Storage	6750	67.5	1500	15	1500	15
Battery	-	-	34.56	0.29	-	-
Facility	1000	-	1000	-	1000	-
Construction	1000	-	1000	-	1000	-
Total	15408	260.05	10158	207.55	6624	207.27

LEVELIZED COST OF HYDROGEN (LCOH)

The non-fixed LCOH is the part of the LCOH attributed to the non-fixed cost, i.e. grid use. The non-fixed part of the LCOH is higher for the non-solar HRS, although this difference is reduced at higher user demands. The default design is also slightly cheaper in nonfixed costs than the improved design. The non-fixed part of the LCOH is however not as important as the fixed part, which, is much larger at low user demands. The total LCOH (Figure 3) shows that the non-solar option is the cheapest, although it is comparable to the improved design. Lifetime and discount rate have a large impact on the outcome of the results; using short lifetimes and high discount rates will always favour systems with lower investment cost. A cost competitive LCOH is assumed to be between 75 - 100 SEK/kg H_2, the user demand required to reach this point is listed in table 4 for six different discount rates and two alterative lifetimes. For high user demands, long lifetimes and low discount rates the improved design becomes more economical over the non-solar design.

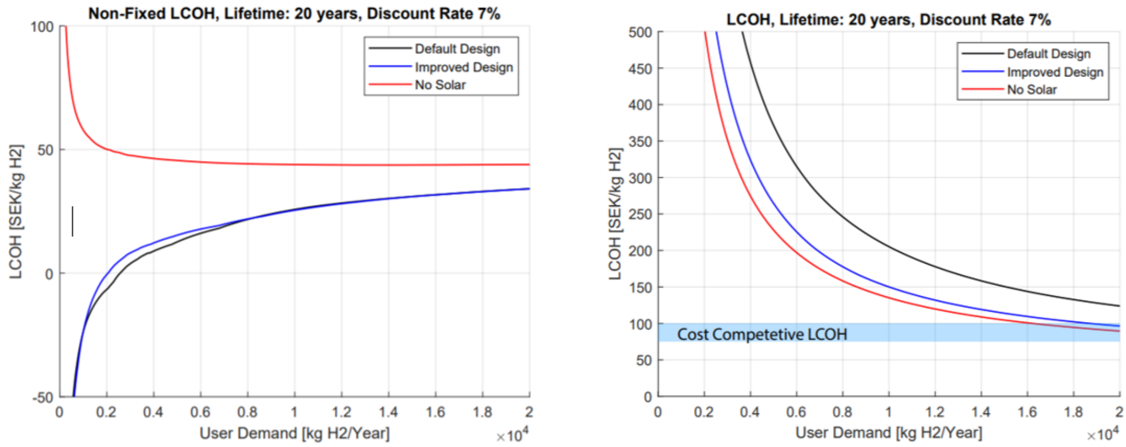

Figure 3: (Left) Non-fixed LCOH; (Right) Total LCOH

Table 4: Break-even User Demand

Discount Rate [%]	Lifetime [years]	Break-even User Demand [kg H2/year]		
		Default	Improved	No Solar
2	20	19420	12830	12360
4.5	20	23820	15590	14190
7	20	28320	18700	16220
2	30	14540	9590	10050
4.5	30	19170	12570	12080
7	30	24620	16000	14370

INFLUENCE OF PRICE VARIATIONS

By looking at the result it is clear that fixed costs have a far greater impact on the LCOH than non-fixed cost. In future scenarios however, it is likely that the fixed costs decrease (components become cheaper and more efficient to manufacture) and nonfixed costs increase (the price of electricity increases). To account for this, a sensitivity analysis was preformed to show how large variations in fixed and non-fixed costs would affect the LCOH of the default HRS design. In figure 5 the results are shown in a scenario where the non-fixed costs are doubled. It was found that as non-fixed costs become a larger part of the total costs and fixed costs a smaller part, the LCOH is less dependent on user demand to become cost competitive. At very low fixed costs a "local minimum" is introduced for the LCOH (around 4500 kg H2 / Year). As nonfixed cost rise in relation to fixed costs the viability and importance of energy storage further increases.

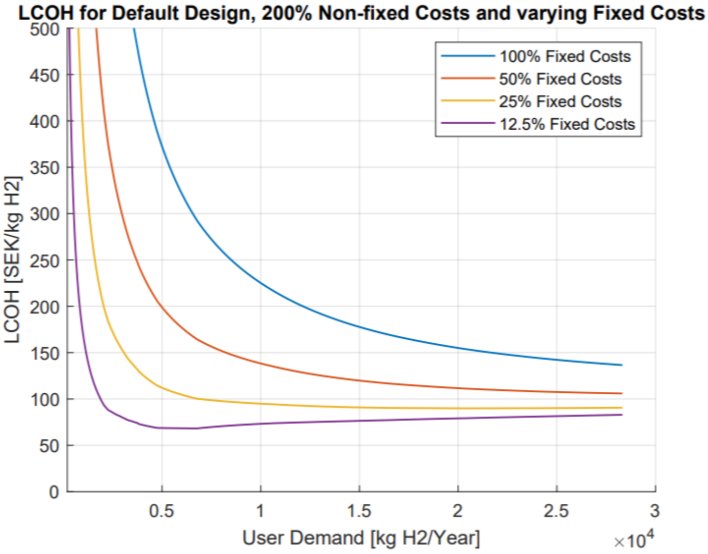

Figure 5: Total LCOH in a scenario where the non-fixed cost are doubled

CONCLUSIONS

The analysis shows that it is difficult for any set-up to be cost competitive at low user demands. The solar options have the advantage of low to negative non-fixed costs at low user demands, however the increased investment cost overshadows this advantage. The precise outcome depends heavily on the assumption of lifetime and discount rate, but the conclusion can be made that finding ways to reduce investment cost is likely going to be more advantageous than any reduction to non-fixed costs is going to be. Cost competitive prices are possible but depend on there being high user demand, regardless of solution. Similarly, the additional revenue from selling excess electricity at low user demands is also not really sufficient to make a significant improvement in the LCOH.