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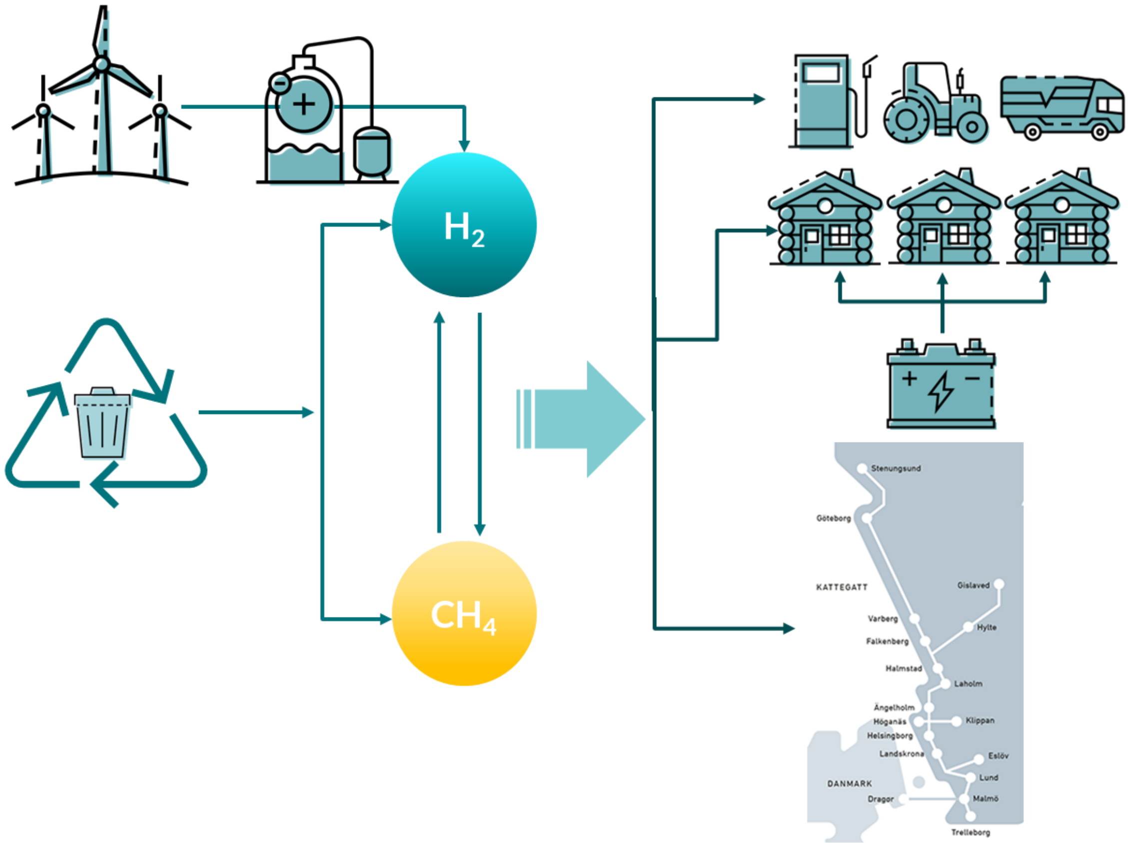

Bioflex - Synergies with electrolytical hydrogen

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Reviewed by: Erika Lönntoft

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Content

Summary

The Bioflex project investigate the compatibility of operation between a two-stage bioprocess and an electrolyser to produce Hydrogen and Methane. Process water from Nordic Sugar in Örtofta, a sugar industry is utilized in the bioreactors. AP2 investigates energy balances and upscaling of the bioprocess, technical compatibility and synergistic effects between electrolysis and the two-step bioprocess. This assignment examines how waste heat from electrolysis can be used to pre-heat process water before entering the bioprocess reactors.

This study analyses three possible configurations of scaled up installation, with a 5MW Alkaline electrolyser and 20m^3 bio-Hydrogen reactor and 100m^3 bio-Methane reactor. The overall efficiency in combined operation mode and stand-alone operation of electrolyser when connection with a high temperature District Heating Network (DHN) are comparable 86-88%. However, under both these cases come with an installation of heat pump which is cost intensive. For electrolyser sizes less than 5MW, water treatment of the seasonal effluent from bioreactors is less energy efficient. Based on pilot study in AP1, the 20m^3 bio-Hydrogen reactor can produce similar amount of Hydrogen as the 5MW electrolyser. The purities of these two methods are different, hence the overall dimensioning of the system would depend on demand and end user for these products.

In the present scenario, with seasonal availability of process water for the bioprocess, the percentage of overlapping working hours of electrolyser and bioreactors varies between 25% to a maximum of 40%. Higher operating hours for bioreactor is recommended to achieve maximum efficiency and consistency of supply.

1 Background

This report presents the work done in AP2: Flexibilities and synergies, by investigating the inter-operability of electrolyser with the two-stage bioprocess. Following AP1, a feasibility study on a scaled-up version of a full-scale installation has been drawn to theoretically examine the mass-energy balance and technical compatibility within the system. The two-stage bioprocess and the electrolyser produce Hydrogen and Methane using process water from Nordic Sugar, a sugar industry. The sugar beet campaign in Örtofta, provides a seasonal production of process water for the bioreactors between September to January. This campaign results in about 13000m^3/day of wastewater from Nordic Sugar. At the moment, this process water from the plant in Örtofta is used as a substrate for only biogas production. This study analyses co-generation of Methane and Hydrogen gas which could be greater valuable products.

Waste heat utilization of electrolysers has been a much-discussed topic for commercial and large-scale electrolysers [1], [2], [3]. In large scale and industrial size electrolysers waste heat utilization has the potential to improve efficiency by 13-15% [3], [4]. In this study, the bio-electrolytic Hydrogen production system is planned to utilize residual heat from an electrolyser for the pretreatment of process water or feed water for the bioreactors. Further, the effluent from the bio-methane reactor is examined for usage in the electrolyser after appropriate water treatment during the sugar beet campaign.

German company GP Joule has an ongoing project, Stromlückenfuller that use heat generated from electrolysis for a biogas digester and buildings [5]. Green Hydrogen Esslingen uses an 1MW Alkaline electrolyser that generates about 600MWh/a of waste heat in addition to 250kg of Hydrogen per day. The heat is used in a district heating grid using a heat pump, a CHP and a peak load boiler [4]. Small scale electrolysers are mostly efficient with just air-cooling and the recoverable heat from them is negligible. The electrolyser capacity, location of heat consumer and transport distance are some critical factors. This is evident from the BioCat project [6], a 1MW installation to produce electrolytic Hydrogen that is further synthesized to methane. Heat recovery from this project was not realized due to lower recovery potential, higher cost of investment for on-site piping and transport of heat to be usable.

1.1 System definition and components

In this study, the pilot setup of a two-stage bioprocess from AP1 is proposed to be scaled up to operate with a 5MW electrolyser. Figure 1 visualizes the interactions in pilot setup as studied in AP1 connected to an electrolyser. A detailed description of the bio-process system can be found in the report of AP1. Upon scaling up, the bio-Hydrogen reactor would require a heating source for pre-treatment of process water from Nordic Sugar. The temperature required is 90°C before entering the bio-Hydrogen reactor to inhibit Methane production. Figure 2 shows a simplified layout of interactions between the bioreactors and the electrolyser.

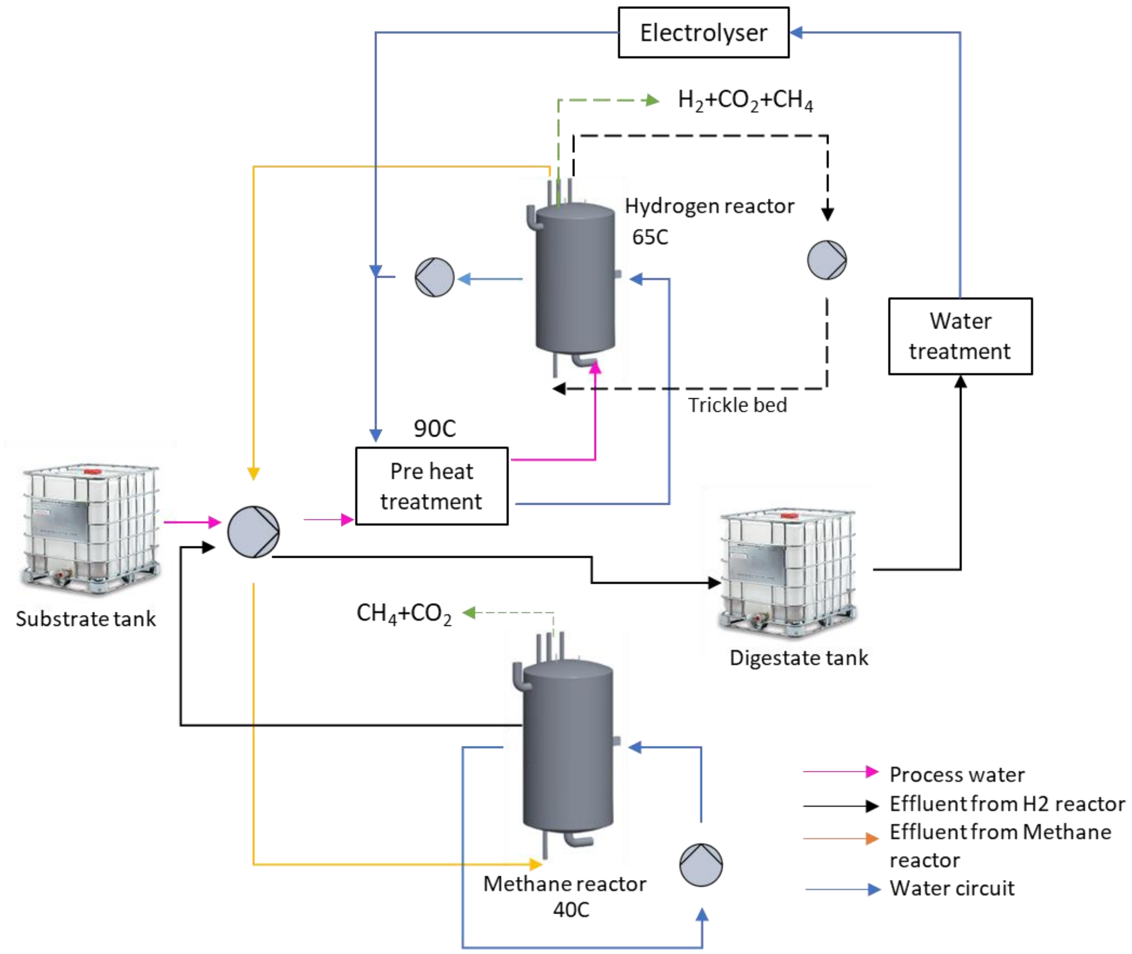

Figure 1 Pilot operation unit from AP2 with addition of electrolyser and Hydrogen components.

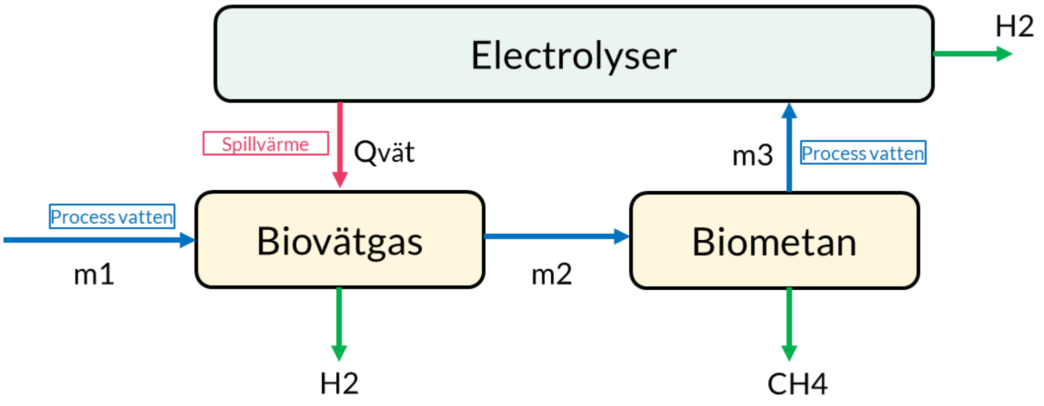

Figure 2 Simplified interactions between bioreactors and electrolyser

2 Method

The project begins with a literature search on existing commercial electrolysers, followed by operational aspects of heat utilization and wastewater treatment requirements. The selection criteria of suitable electrolyser for this study depends on operational temperature, resilience to intermittent supply of electricity and demand, degree of water purity required for operation etc. Possible configurations of the 5MW electrolyser operating along with the bioreactors are proposed based on a first order mass and energy balance. Finally possible operational scenarios are analysed for the net positivity of the system across the year.

2.1 Commercial electrolyser technologies

Electrolysers can be classified based on operational temperatures as low and high temperature technologies. Low temperature electrolysers include Proton Exchange Membrane (PEM), Alkaline Water Electrolysis (AWE) and the Anion Exchange Membrane (AEM) which is under development. Operating temperatures of PEM are 20-80°C, AWE 40-90°C and 40-60°C for AEM electrolysers. Solid Oxide Water Electrolysis is considered a form of high temperature electrolysis which operates in the range of 700-to-1000-°C [7].

Demo4Grid project has a 4MW Alkaline electrolyser in Völs, Austria. The electrolyser from Sunfire Gmbh is used for grid services and supply of Hydrogen as fuel for a food production plant [8]. Fukushima Hydrogen Energy Research Field (FH2R) has a 10MW alkaline electrolyser installed in connection with a 20MW solar park [9]. Larger alkaline electrolysers in the scale of 100MW are also under investigation within EU, as seen in ongoing GREENH2ATLANTIC project [10]. In the HySynergy project in Denmark 20MW is planned for Hydrogen supply to Crossbridge energy refinery and heat to DHN [11]. Cummins's modular alkaline electrolyser system has several versions of Hystat that can produce between 21kg/h to 189kg/h hydrogen at 99.99% purity [12].

In this study, an Alkaline electrolyser is chosen since it meets temperature range for the bioprocess, is a mature technology and is less expensive than PEM technology. AWE can handle intermittency to electricity supply well when operated between limited power ranges. However, AWE is comparatively more suited for constant load applications to avoid cross-diffusion of gases within the electrolyser [11], [7]. Main limitations of AWE are the chances of Hydrogen contamination, corrosion due to highly corrosive electrolyte [9].

2.2 Heat recovery potential

In the overall bioprocess and electrolyser system the heat requirement is in the pre-heat treatment section before the feed water enters the bio-Hydrogen reactor. Currently in the pilot scale setup, a heat exchanger is used to pre-heat the feed water (process water from Nordic Sugar) to eliminate the methanogens before entering the Hydrogen reactor. The temperature requirements in different stages are pre-heat treatment 90°C, operating temperature of bio-Hydrogen reactor is 65°C which further drops to 40°C in the operation of the bio-Methane reactor as shown in Figure 1.

2.2.1 Operation and stack degradation of electrolysers

The heat dissipated from electrolysers varies over time, gradually increasing over the years of operation with stack degradation. On the other hand, the energy consumption from the beginning of life increases. Stack degradation is defined as a percentage of loss in efficiency over normal operating hours. According to Fuel Cell Hydrogen Joint Undertaking (FCHJU), degradation percentage per 1000 hours of operation for 2024 standards, has been targeted to be 0.125 [13]. Over the lifetime of the electrolyser in 10years, there will be an increase of 10% of energy consumption. According to Cummins, the efficiency degrades by less than 1% per year when an assumption of 8,500 hours of operation is taken [14].

Heat production from a 2.5MW electrolyser could vary by 5-10% between Beginning Of Life (BOL) and End Of Life (EOL) when operating for 10years and a maximum of 80% of this heat can be recovered. Favourable operational conditions include operating at least at 75% of its installed capacity and at least 6500 full load hrs/year. This accounts issues related to availability of renewable power, source of water around the year in the location of the bio-electrolytic system. The minimum load for electrolysers is limited to be 10% since the stack efficiency of electrolyser drops significantly when the electrolyser load decreases further. The efficiency of present-day electrolysers is 74-79% [15], [16], this can be further improved with optimal heat recovery.

2.2.2 Sources of heat recovery

During the operation of an electrolyser, heat can be recovered from different sources which include the stack, the Oxygen and Hydrogen stream which also contain water vapour after exiting the stack [3], [17]. According to [15], 14-15% of the electricity input to the stack can be extracted for heat utilization and the stack is the core source for heat extraction. Heat recovery potential when operating under 70-80% stack efficiency (HHV) is 9.3-16.7kWth/kgH_2 [18]. Other operations regarding Balance of Plant (BoP) processes are difficult to extract for ex. demineralisation of water, therefore they are excluded from the study. In our analysis we limit heat extraction to the stack which includes electrolyte (Lye), Oxygen and Hydrogen streams and assume no recoverable heat can be obtained from other ancillary equipment.

Commercial electrolyser units come with an internal heat exchanger or a dry cooler circuit that is inbuilt to maintain the operating temperature of the stack. This dry cooler circuit also functions as a redundant cooling circuit in case of low heat demand from end user. It regulates the temperature of the Oxygen + water, Hydrogen + water streams that come out of the electrolyser stack. An overview on heat recovery streams in a PEM electrolyser is analysed where the outlet temperature is 57-62°C [15]. The pre-heat treatment required before entering Bio-Hydrogen reactor is 90°C, therefore an AWE electrolyser is suitable for our study. Three possible ways of heat recovery from electrolysers are via passive cooling, evaporative cooling and thermal recovery [19]. Current scale of commercial electrolysers can be managed with passive cooling alone, however for current study upon upscaling electrolyser, a separate cooling circuit is necessary.

2.3 Wastewater treatment for feedwater to electrolyser

Water treatment literature is less abundant for treating process-water than compared to salt water or brackish water. One of the reasons being the composition of these process water/ industrial wastewater is often based on the source. The treating process must be designed according to the composition and level of purity required for the subsequent processes. Careful consideration of feedwater to electrolyser is essential to avoid scaling, corrosive reactions or increased maintenance costs, faster degradation etc.

Water quality based on [20], a review on impurity sources, water purification techniques and outlines operational mechanisms for electrolysers. Electrolysers need to be operated above thermoneutral voltage to overcome losses in electrochemical reactions. This in turn creates excess heat that needs to be extracted.

2.3.1 Qualitative requirements

Electrolysers require purified water that have a very high resistivity, meaning a low concentration of charge carrying ionic species [20]. Inlet water to electrolysers demand high purity, these requirements are mentioned in terms of minimum resistivity 1 M ohm cm and Total Organic Carbon (TOC). FCH2JU has published EU protocols [7], for testing low temperature water electrolysis (PEM, AWE, AEMWE).

De-ionization of water is an energy and capital-intensive process in the production of Electrolytic Hydrogen. The deionization water circulation system comprises of an oxygen separator tank, circulation pump, piping, valves and instrumentation and controls. These accounts for about 20% of BoP of 1MW electrolyser and this cost share increases to 32% for a 200kW system. Similar cost trend applies to Hydrogen processing and cooling units which makes smaller scale systems overall more expensive [21]. Some references for purity of water are ASTM D1193-06 Type I water and ISO 3696 Grade 2 water [7]. Quality of water in terms of purity and necessary purification techniques are often proprietary to manufacturers.

2.3.2 Quantitative requirements

Electrolysers operate at least 6500hrs on full load, this requires a continual supply of feedwater throughout the year. Nordic Sugar’s sugar beet campaign from September to January yields a seasonal production of wastewater of about 13000m^3/day or 13million L/day [22]. Due to the seasonality of this source, the electrolyser would need an alternative water source from for example groundwater or surface water, city municipal water.

Water requirement for 1MW electrolyser according to [18], is 200L/h ultrapure water. Large scale electrolysers require about 30-50L of ultrapure water for producing a kilogram of hydrogen [19]. Assuming 6500hours of full load operation in a year, the amount of water required in a year for electrolysis is = 200*6500 = 130,000L/yr. Furthermore, the volume of water required for cooling as in [18] is 400L/h, due to heat utilization in the bio-process system the cooling water requirement would vary from case to case.

Silhorko-Eurowater A/S estimates the volume of raw water required to produce 1m^3 of ultrapure water varies based on source for example 1.4m^3 of groundwater, 1.5m^3 of treated wastewater or surface water and 3.3m^3 of seawater [23]. Table 1 shows water and energy requirements for operation of a generic 5MW installation.

Table 1 Water and energy requirements for a generic 5MW electrolyser [18]

Electrolyser size	**5MW**
Specific energy consumption	45-55kWh/ kg of Hydrogen
Ultrapure water requirement	1000L/h
Raw water requirement	1500L per 1000L of Ultrapure water
Cooling water requirement	400L/h per MW
Energy consumption for treating 1000L of treated wastewater	2.2kWh

Companies such as CleanTEQ water and Eurowater AB provides demineralization and water treatment systems specific for Green Hydrogen production for 1-10MW plants, from different sources including wastewater and municipal water. For the real-scale installation, feedwater to electrolyser must be checked for a full chemical analysis including amounts of suspended solids, Total Organic Carbon (TOC), silica content etc. [18].

3 Mass and Energy Balance

This section focuses on the heat utilization from electrolyser, process water treatment for feed-in to the electrolyser. Mass and energy balance calculations analyse different configurations of heat recovery that include, setups with and without heat pump, under different operational modes for the electrolyser and the bioreactors over the year. Parameters such as heat recovered from different streams from the electrolyser, system efficiency etc. are calculated in this section for a commercial 5MW Alkaline electrolyser installed in connection with possible dimensions of Bio-Hydrogen reactor (80m^3) and Bio-Methane reactor (400m^3).

3.1 Commercial scaling of system

A possible layout of a commercial scale bio and electrolyser-based system is shown in Figure 3 based on reference model demonstrated in project HycoGen [17]. The size of commercial scale biogas reactor in Nordic Sugar is 20000m^3. The setup could be scaled to a Bio-methane reactor of size 400m^3 available at Indienz fermentation company. To maintain a Hydraulic Retention Time (HRT) of 40h for this size the flow rate is taken as 25m^3/h accounting transport losses. The bio-Hydrogen reactor can be scaled to 80m^3 consistent with the ratio of reactor sizes in the pilot scale study in AP1. Small scale electrolysers have reduced heat recovery potential and high investment cost for heat transfer components resulting in overall low efficiency and high levelized cost for the heat recovered.

The temperature of this process water from Nordic Sugar depends on a variety of factors such as weather conditions, location of storage indoor or outdoor and duration of storage in the tank. Net amount of heat extracted also depends on the transport distance of pre-heat treatment chamber from the electrolyser. On average the temperature drops by 2°C per 200m according to [15]. Note that for electrolyser operation in the stack deionized water is required but for the cooling tower demineralised, this is an assumption made in this study.

3.1.1 Case 1: Both Electrolyser and bioprocess reactors operate

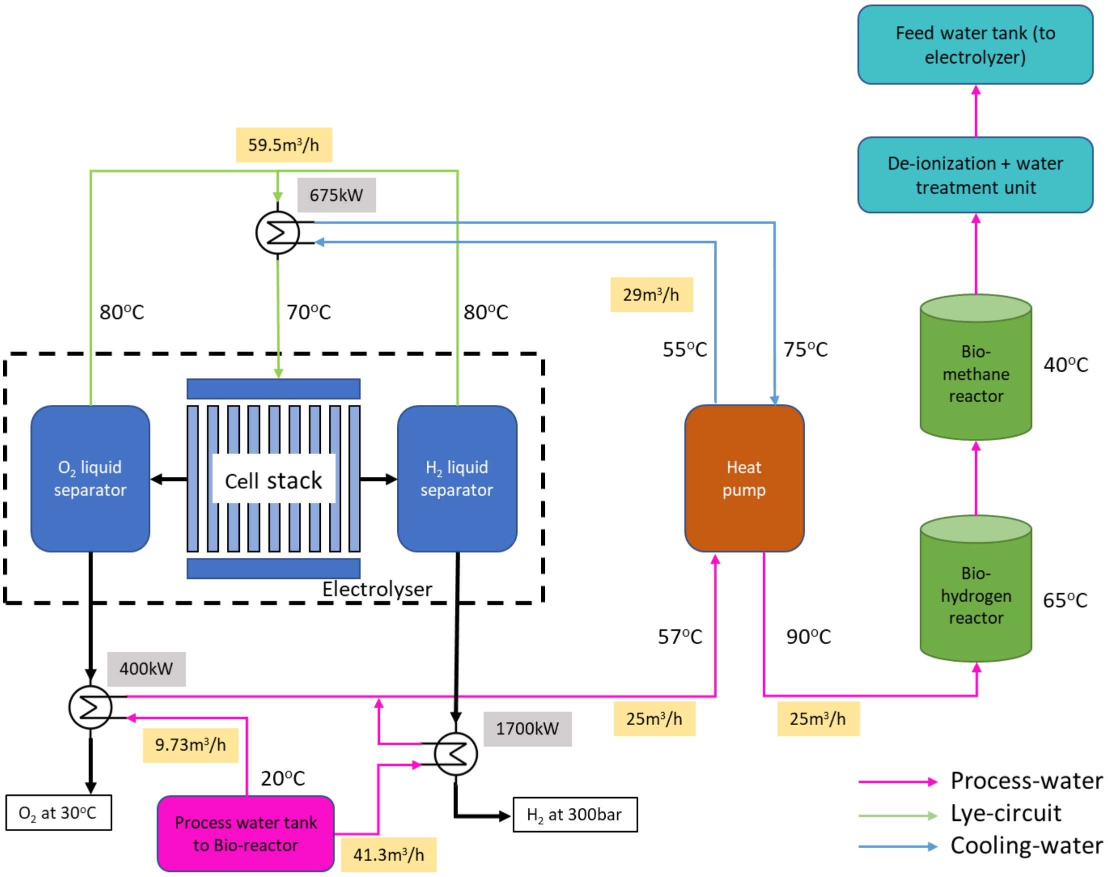

Figure 3 Process flow of Bio-electrolyser system with only heat pump

Project HyCoGen demonstrates recovery of heat from a 20MW electrolyser that produces 400kg/h hydrogen. Figure 3 shows a possible layout for co-operation of bioprocess reactors with a smaller alkaline electrolyser of 5MW using HyCoGen as reference [17]. Case 1 proposes that the heat extraction is possible from all the three streams of the electrolyser: Hydrogen stream, Oxygen stream and the electrolyte circulation streams around the stack. The heat recovery from the cell stack is done through a separate coolant water loop which runs at high mass flow rates to maintain the temperature differential across the stack [23]. Further this coolant water is used in the heat pump to transfer the heat to the process-water before entering the bio-Hydrogen reactor at 90°C.

During the beet campaign between September to January the residual heat from Oxygen and Hydrogen streams is utilized in pre-heating the process water and subsequently in the heat pump. This situation goes well with Case 1 when both the bioreactors and the electrolyser are operational. The residual heat from the Hydrogen stream can be extracted from several stages such as the Hydrogen purification system, first stage compression 1-30 bar and second stage compression 30-300bar. A cumulative cooling load of 850kW is modelled for the Hydrogen stream and 200kW for the Oxygen stream after they pass through the liquid separators. The re-circulation loop to the electrolyser stack flows at 70°C through an agitation process [24].

Using a cooling water circuit to extract heat from the lye-circulation loop, the coolant water temperature can rise to 75°C. To achieve this, the cooling water exchanges heat at the anode and cathode electrolyte recirculation loops at high mass flow rates. Figure 4 shows heat exchange between streams in the heat pump.

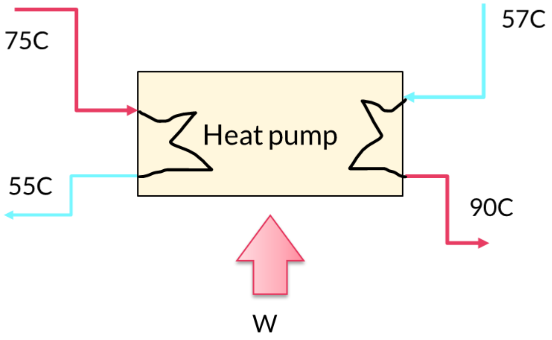

Figure 4 Energy balance for heat pump

Heating required for the process water (57 to 90°C) $Q_{\mathrm{H}} = \dot{m}_{\mathrm{process}} Cp\Delta T$

Assuming Cp for the process water is slightly less than pure water 4kJ/kgK and density is 1030kg/m^3. To achieve an HRT of 40h in the biomethane reactor, $\dot{m}_{\mathrm{process}}$ = 25m^3/h or 7.15kg/s for a reactor volume of 1000m^3.

Heating required = Q_{H} = 7.15*4*(57-90) = 943.8kW

$$\dot{W} = \dot{Q}_H - \dot{Q}_L = \frac{\dot{Q}_H}{COP} \rightarrow \dot{Q}_H = \frac{COP*\dot{Q}_L}{COP-1}$$

……. Eqn.[x]

$$\dot{\mathrm{W}} = \mathrm{QH} - QL = \frac{\mathrm{QH}}{COP}$$

At COP = 3.5 for the heat pump, Input work required for the heat pump is calculated from equation [x], as W = 943.8/3.5 kW = 269.6kW

Cooling required is $Q_{\mathrm{L}} = Q_{\mathrm{H}}$ - W = 943.8 – 269.6 = 674.2 kW

Mass flow rate of cooling water can be calculated from the equation,

$Q_{\mathrm{L}} = \dot{m}_{\mathrm{coolingwater}} Cp\Delta T$

$\dot{m}_{\mathrm{coolingwater}} =$ 29.0m^3/h or 8.06kg/s

Heat capacity of Lye = 3.101 kJ/kg K (at 30% aq.KOH) [24], density of Lye is 1309.7kg/m^3. Using the cumulative capacity of heat exchanger required between Lye-coolant water junction is obtained as 675kW. This will be implemented as two heat exchangers one each for anode and cathode recirculation loop of equal capacity say 350kW. The mass flow rate in Lye-circulation loop is maintained using centrifugal pumps. The consumption of ultrapure water for electrolysers according to [23] is 0.2m^3/h for 1MW electrolyser and about 9L/kg of Hydrogen. In the current plant, for 5MW electrolyser 1m^3/h of ultrapure water is required to produce 100kg of H_2/h.

The sugar-beet campaign is from September to January and the setting time for reaching steady state is about 60 days for the pilot scale setup. Assuming with dedicated systems, the steady state reaches quicker in the real scale installation. The percentage of overlapping working hours of electrolyser and bioreactors varies between 25% to a maximum of 40%. Therefore, the subsequent cases 2,3 are proposed where the electrolyser dissipates heat to the district heat network. Nordic Sugar already has a connection to district heating so this option can be utilized. To use output Hydrogen an output pressure of 300bar is necessary and this poses the requirement for compressors [17].

Compressor loads are taken to be 0.2 MW for each stage of compression of Hydrogen gas from 1-30bar and 30-300bar. Pump load is taken to be approximately 0.1MW in the system. Electrolyser load varies over the years due to degradation and input power deviation is taken to be 20%, hence the electrolyser load is between 5MW to 6MW.

Table 2 Energy balance for case 1

Electrical loads	(MW)	Description	(MW)	Losses	(MW)
Electrolyser load	5	Hydrogen produced HHV	4	Loss to environment	0.5
Pumps	0.1	Heat recovered Oxygen stream	0.2	Oxygen 30-20C	0.15
Compressor loads	0.4	Heat recovered Hydrogen stream	0.85	Loss to ambient from heat pump	0.05
Heat pump	0.26	Heat obtained from heat pump	0.943		
Misc.	0.35	Heat recovered from Electrical equipment cooling	0.1		
		Heat pump cooling	0.267		
		Total	6.39		0.7
		Efficiency	89%		

Efficiency = 89% (BOL)

In all the three operational cases, over the lifetime of the electrolyser the electrolyser efficiency at BOL may further increase by 1-2% towards the EOL [15], [17]. As a next step, two possible Bio-reactor dimensioning cases are proposed. Possible installation 1, could be at Indienz that has a 400m^3 reactor, in combination with a 80m^3 Bio-Hydrogen reactor. Possible installation 2, could be a 100m^3 and 20m^3 setup which produces almost the same amount of Hydrogen (kg/h) as the 5MW electrolyser. The choice of selection between these two dimensions depends on the demand for Hydrogen and optimal storage tank at the site. It is important to consider purification losses for Bio-Hydrogen while scaling up. The scaled-up estimate of Hydrogen and Methane production from the two bioreactors under the pilot setup is shown in Table 3.

Table 3 Possible Methane and Hydrogen production with scaled-up model

Gas	Pilot scale	Installation1 400m^3 : 80m^3	Installation 2 100m^3 : 20m^3	Gas	Electrolyser (5MW)
	L/Lr/day	Kg/h	Kg/h		Kg/h
Methane	0.91	940.5	235.1	**Oxygen**	800
Hydrogen	1.57	435	108.7	**Hydrogen**	100

3.1.2 Case 2: Only electrolyser is operational, heat utilized by low temperature DHN

During off-season times from February to August when the process water input for the bioreactors is not available, case 2 considers the operation of only electrolyser in connection with a modern low temperature District Heating Network (DHN). This setup can function with a heat exchanger and a cooling tower that dissipates the excess heat. This model is an alternative to operating the heat pump at high electricity prices during February and early spring for example. Several configurations of heat retrieval are also possible by utilizing the heat pump at high COP or lifting the DHN much higher using optimised cooling networks within the system. This study only provides a first order design of heat extraction and cooling pathways within the bio-electrolytic Hydrogen production process. Therefore, this design may be further optimised. Figure 5 shows a possible setup for case 2 with a heat exchanger installation to supply to a low-temperature DHN. The red line represents the hot stream and blue represents cold stream in Figures 5 and 6.

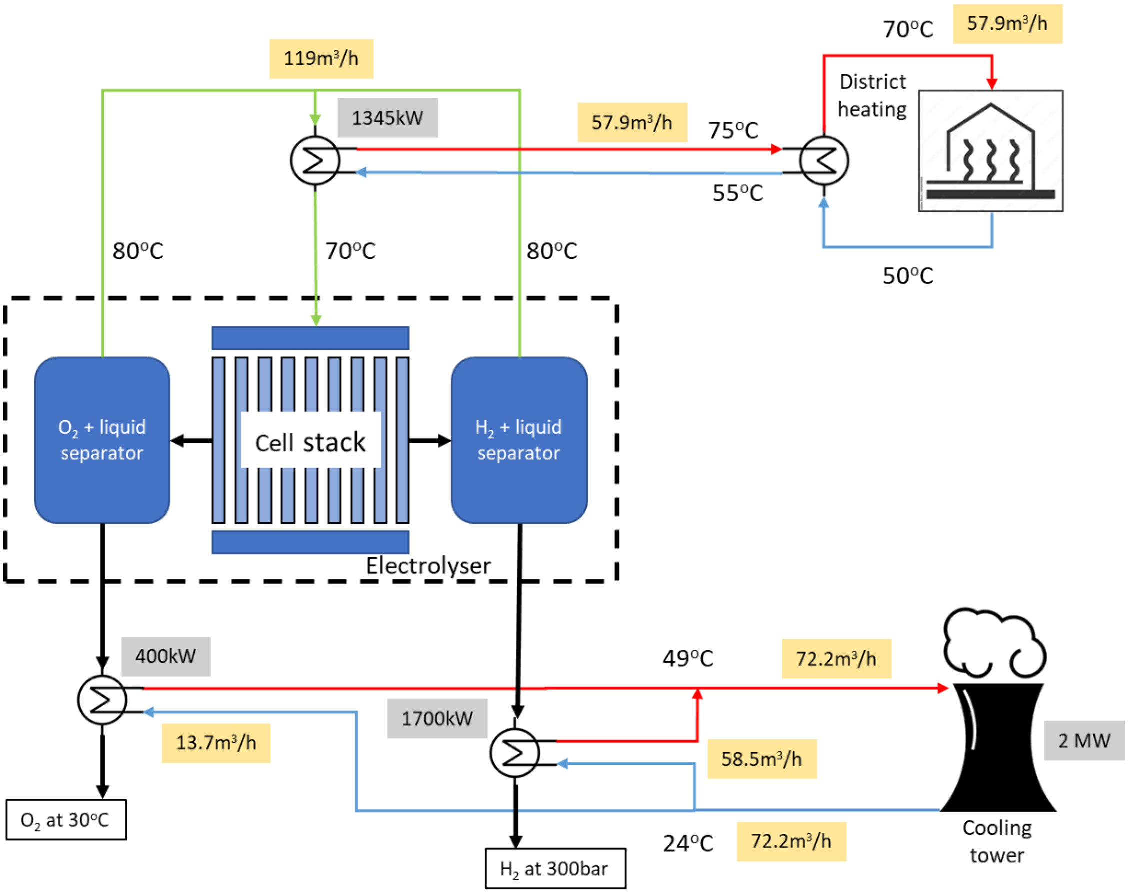

Figure 5 Possible setup with heat exchanger and low temperature DHN

An external cooling circuit runs through the Oxygen and Hydrogen circuit to cool down components using cooling water at 24°C. This is supplied from an external cooling tower of 2MW cooling load. In this configuration, electricity costs through not operating heat pump can be saved, however there is a need for an additional heat exchanger. The output temperature that can be obtained is around 70 °C which can be further spiked through a boiler or through residual heat from sugar production processes to join a higher temperature DHN. Nordic Sugar at Örtofta already has connections with DHN providing a significant annual consumption [25].

Heating recovered from Lye-circuit to low temperature DHN is

Mass flow rate is of DHN loop is taken as 57.9m^3/h which is 16.08 kg/s

Q_H = 16.08*4.18*(70-50) = 1345 kW or 1.34MW

Table 4 Energy balance for Case 2

Electrical loads	**(MW)**	**Description**	**(MW)**	**Losses**	**(MW)**
Electrolyser load	5	Hydrogen produced HHV	4	Loss to environment, oxygen	0.5
Pumps	0.1	Heat recovered from Lye-circuit	1.34	Oxygen 30-20°C	0.15

Electrical loads	(MW)	Description	(MW)	Losses	(MW)
Compressor loads	0.4	Heat from Oxygen stream	0.2	Heat lost Oxygen stream	0.2
Misc (Demister, Oxygen 30 to 20, electrical cooling etc.)	0.35	Heat from Hydrogen stream	0.85	Heat lost Hydrogen stream	0.85
		Heat recovered from Electrical equipment cooling	0.1		
		Total	6.49		1.7
		Efficiency	73.8%		

The efficiency in this case is much lower since the heat from Oxygen and Hydrogen streams are not utilized. The heat provided to the low temperature DHN may be higher with optimized mass flow rates of the DHN return. The heat retrieved (1.34MW) may supply a standalone low temperature district heating network or as process heat in the sugar industry. Alternatively, this case can also be an option for the future in case the bioreactors could work with an alternative strain of microorganisms that can function at lower temperature and not in need of pretreatment at 90°C (say 70°C).

3.1.3 Case 3: Only electrolyser is operational, high temperature DHN.

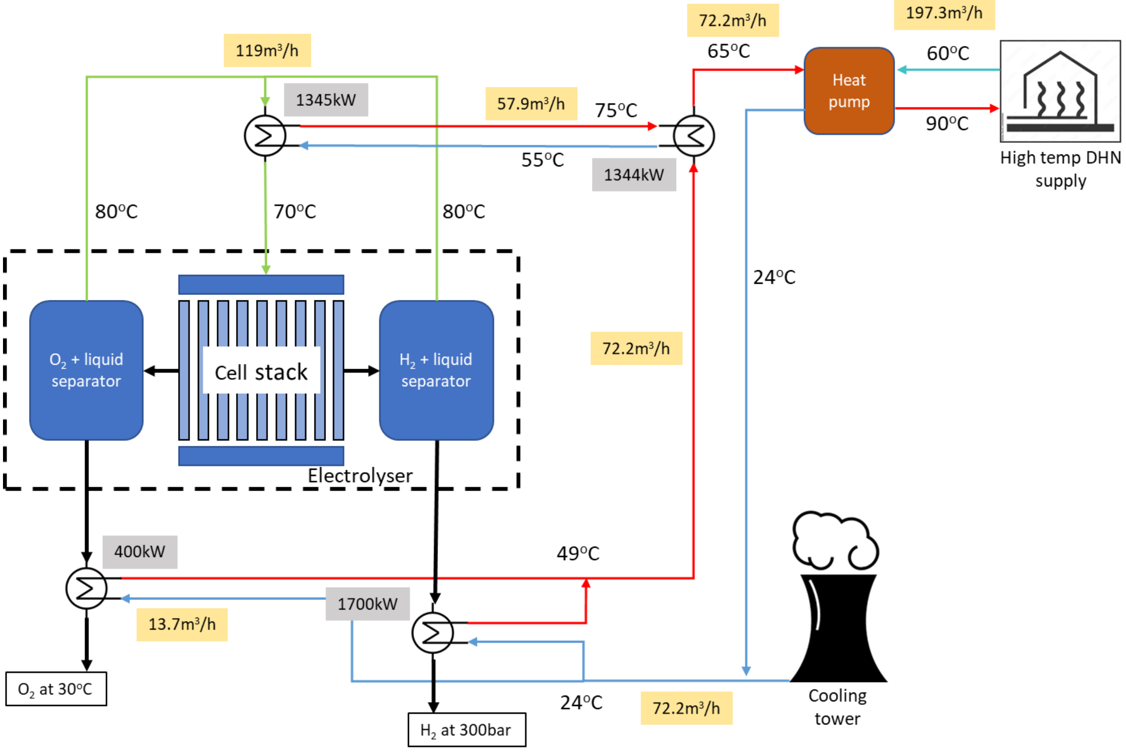

Figure 6 Possible setup with heat pump and high temperature DHN

This case considers that only the electrolyser is operational, and the extracted heat is utilised in a heat pump to further increase temperature to feed into a high temperature DHN. Figure 6 shows a possible layout that can supply to DHN at 90°C. This case is motivated instead of investing in cooling tower, but to cool down all the three streams to heat up a high temperature DHN and obtain revenue from selling heat.

Cooling water at 24°C is used to extract residual heat from the Oxygen and Hydrogen streams to reach 49°C. The heat extracted from the electrolyte circulation loop from the stack is used in a heat exchanger to further heat this cooling water to 65°C. This heated stream is now used in a heat pump to heat up the DHN supply. This setup assumes that the heat pump functions at lower efficiency (COP=2) due to the high temperature difference between the hot and cold streams [26]. As a result, the heat potential to DHN is about 6.8MW BOL. The heat potential at EOL can be up to 1.5 times the heat produced at BOL [17].

Energy balance for the heat pump, $W = Q_H - Q_L = Q_H/COP$

$Q_H = 6.8MW$, $Q_L = 3.43MW$

Work required to operate the heat pump is 3.43MW

Table 5 Energy balance for Case 3

Electrical loads	(MW)	Description	(MW)	Losses	(MW)
Electrolyser load	5	Hydrogen produced HHV	4	Loss to environment, oxygen	0.5
Pumps	0.1	Heat recovered Oxygen stream	0.2	Oxygen 30-20C	0.15
Compressor loads	0.4	Heat recovered Hydrogen stream	0.85	Loss to ambient from heat pump	0.30
Heat pump	3.43	Heat obtained from Heat pump	6.86	Losses in transfer to DHN	0.5
Misc	0.35	Electrical equipment cooling	0.1	Losses in cooling tower circuit	0.2
		Total	12.0		1.47
		Efficiency	87%		

Efficiency = 87% this may further increase by 1-1.5% by EOL.

The efficiency of this case is lower than case 1 due to the lower COP of the heat pump, but higher than case 2 since in this configuration all the streams have been heat extracted. Revenue from the heat energy sold to the DHN at high temperature is expected to reduce the overall Levelized Cost of Hydrogen (LCOH) to produce 1kg of Hydrogen.

4 Discussion

The following operational scenarios are discussed to look at interoperability and effects of scaling-up the system.

4.1 Combined operation mode

This scenario corresponds with Case 1, the overlap in operational period, the COP of the heat pump, mass flow rate of process water entering the heat pump decide the overall heating achieved in the bioreactors. Ultra-pure water requirement for 5MW electrolyser considerably is 1000L/h, in case of smaller electrolyser dimensions water treatment is an energy intensive and cost intensive process [18]. Instead, a city municipal water source or a surface water source would be a better and consistent solution year-round.

The purities of Hydrogen from the electrolyser and the bioreactor are different and therefore suitable end users or an investment in purification systems is necessary.

Hydrogen and Oxygen produced though Alkaline electrolysis have a very low level of contaminants where the final hydrogen purity can reach 99.99%. Standards such as Fuel Quality Standards ISO 14687-2019 define compliance for Hydrogen to be used in fuel cell automotive applications and fuel cell stationary applications [7]. Potential end users for Hydrogen may be for example refineries, industries that have constant base load and seasonal peaks in a year.

Alternative microbial cultures that can work with slightly lower temperatures may be suitable for other types of electrolysers for example PEM that has outlet temperature of 65°C. Through scaling up to industrial scale, the variation of ageing of electrolysers needs to be accounted for to calculate the extractable heat. Stacks may be of different stages in their lifetime resulting in varied heat produced based on degradation and aging. Based on AP1, the Hydrogen reactor takes at least 2-3months for the start-up and gets a stable yield of H_2. The mass flow rates in the system have been designed based on a HRT of 40h, efficient production 2-3days [27]. However, the system may be further optimized for heat utilization and HRT depending on the need.

4.2 Standalone operation of the electrolyser system

This operational mode corresponds to cases 2 and 3 of this study. The composition and COD strength of the process water fluctuates throughout the year and this can cause system instability as said in AP1. It is to be noted that the water-treatment techniques must be tolerant to this variation to prevent degradation of the electrolyser [28]. During times other than the beet campaign the electrolytic system needs a constant external water source from nearby water bodies or any other consistent industrial provider which produce process water of characteristics similar to Nordic Sugar or that can be treated with existing water treatment systems.

4.3 Stand-alone bio-process mode

This scenario is considered when the electrolyser is under planned maintenance or under unplanned interruptions to operation. Under these situations the bioprocess system will pose a significant heating load (approximately 0.95MW as seen in Case1) for pre-treatment. This needs to be obtained from an external heating source otherwise these hours must be scheduled during the summer months of Sweden to avoid excess electricity costs. The heating source may be residual heat from sugar production plant or a boiler that runs on produces fuels. Through a further environmental assessment can investigate suitability of using bio-methane for heating.

5 Results

The proposed three different operational configurations for the bio-electrolytic system showcase the theoretical analysis of co-production of Methane and Hydrogen from the two-step bioprocess and electrolyser. This work package does not claim a complete analysis of energy and mass balance, but rather shows possible configurations of heat utilization in different operational scenarios. Some major conclusions

- The overall efficiency in combined operation mode (Case 1) and stand-alone operation of electrolyser (Case 3) are comparable. However, under both these cases come with an installation of heat pump which is cost intensive.

- Oversizing of the bioreactors may result in high seasonal production of Hydrogen when run in combination with electrolyser. Therefore, a control strategy must be developed for parallel production and storage of electrolytic and bio-Hydrogen. For example, the electrolyser will need to run at lower capacity factor when bioreactors are operational. Suitable end users are to be selected to utilize produced Hydrogen and minimize intermittency to electrolyser operation.

- In the present case, with seasonal availability of process water for the bioprocess, the percentage of overlapping working hours of electrolyser and bioreactors varies between 25% to a maximum of 40%. Higher operating hours for the bioreactors are recommended to achieve maximum efficiency.
- For electrolyser size less than 5MW, water treatment of the seasonal effluent from bioreactors is not energy efficient.

Further, optimal sizing of the system components and heat exchange circuits would be based on following factors: demand for Hydrogen locally in Eslöv and surrounding areas, location of end user, readiness of Hydrogen distribution and storage infrastructure, location and spatial constraints etc.

6 Future work

An optimal schedule must be developed for the co-operation of the bioreactor and electrolyser system to be able to dimension the Hydrogen storage and distribution infrastructure. A full-scale chemical analysis on water quality has not been performed in this study due to unavailability of sample of effluent from the bioreactors. Feasibility and energy intensity of water treatment for electrolyser has not been elaboratively analysed, it is suggested for future work.

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