Economy vs sustainability: comparison of the two operational schedules for the hydrogen-based energy management system with P2X demand response

Klyapovskiy, Sergey; Zheng, Yi; You, Shi; Bindner, Henrik W.

Publication date:
2020

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Klyapovskiy, S., Zheng, Y., You, S., & Bindner, H. W. (2020). *Economy vs sustainability: comparison of the two operational schedules for the hydrogen-based energy management system with P2X demand response*. Paper presented at International Conference on Applied Energy 2020, Bangkok, Thailand.

International Conference on Applied Energy 2020
Nov. 29 - Dec. 2, 2020, Bangkok, Thailand
Paper ID: xxxx

Economy vs sustainability: comparison of the two operational schedules for the hydrogen-based energy management system with P2X demand response

Sergey Klyapovskiy[1*], Yi Zheng[1], Shi You[1], Henrik W. Bindner[1]

1 Center for Electric Power and Energy (CEE), Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark

ABSTRACT

Hydrogen production could be used to consume excessive renewable energy. Many energy management systems (EMSs) were proposed to link hydrogen production with renewable farms. The majority of the studies, however, are not based on the real-life systems and do not fully utilize the potential of demand response from P2X components. In this paper, we propose an EMS architecture based on the GreenLab Skive industrial cluster that can operate the system with default, economic (minimize operational costs) and sustainable (produce green hydrogen) schedules. EMS utilizes the flexibility from electrolyzer, hydrogen tank, battery and hydrogen consuming plants (HCPs) to provide an optimal dispatch in economic and sustainable schedule; operating the system in either of them results in operational costs reductions in comparison with default schedule. The hydrogen produced with the sustainable schedule is green and such operation could serve as a backbone of the future sustainable energy system.

Keywords: electrolyzer, P2X, energy management system, sustainability, green hydrogen

NONMENCLATURE

Abbreviations	
DR	Demand response
EMS	Energy management system
GLS	GreenLab Skive
HCP	Hydrogen consuming plant
P2X	Power to X (here gas)
SoC	State of Charge
Symbols	
C_{ext}, C_w, C_p, C_{scf}, C_b, C_{ele}, C_{H_2}	Costs of power/hydrogen from different components, [€]
I_b, Q_b	BESS current, [A] and maximum capacity, [Ah]
M_{H_2}	Stored hydrogen in the tank, [mol]
P_{ext}, P_w, P_p, P_{sfc}, P_l, P_b, P_{ele}, P_{pro}	Active power from external network; wind turbines; solar panels; secondary flexible components; uncontrollable loads; BESS; electrolyzer and protein plant [W]
ΔP_{sfc}	Active power reduction due to DR from secondary flexible components, [W]
$q^{ds}_{H_2,i}, q^{rs}_{H_2,i}$	Hydrogen consumption of HCP i [kg/s]; ds for default schedule and rs for rescheduled
Δq_{H_2}	Hydrogen mass flow rate after covering HCPs demand, [kg/s]
WT, SP, SFC, L	Total number of wind turbines, solar panels, secondary flexible components providing DR and uncontrollable loads, [-]

1. INTRODUCTION

Hydrogen becomes the "next big thing" in sustainable energy systems. In a span of a year, many private companies - independently or with public support - have announced their large-scale hydrogen projects [1,2].

Hydrogen production could absorb excessive renewable energy; both researchers and engineers expect that such flexible electrical load will drive the renewable energy integration to a new level [3]. To facilitate integration, a decision-making platform - an

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

EMS handling energy and information flows and issuing commands to different system components - is needed. Many studies describe various hydrogen-based EMSs [4,5]. However, only a few of them are based on real-life industrial systems with hydrogen and they do not take advantage of the DR from the P2X components. In addition to that, there is a need for more research regarding how the potential green hydrogen production – made entirely by renewable energy – will affect the system's overall costs compared to the system following default (conventional) or economic schedules. This difference could, in the future, lay on the customers' shoulders, if the energy system continues on the path for sustainability.

Based on the identified gaps, the main contributions of this paper are as follows:

- We proposed EMS architecture and formulated optimization problem that are based on the real-life system of GLS - referred by some as the first green industrial business park [6];
- We included P2X DR from HCPs present at GLS to enhance the flexibility potential of the system;
- We demonstrated the benefits the system gets from following either economic or sustainable schedule and compared them between each other and with the default schedule operation.

2. ENERGY MANAGEMENT SYSTEM

2.1 *GreenLab Skive industrial cluster*

GLS is an industrial park that utilizes the idea of industrial symbiosis [7], where residual resources from one plant are utilized at another.

There are seven industrial plants located at GLS producing: oil from pyrolysis, methanol, compressed hydrogen, hydrogen, methane from biogas, recycled waste, and marine protein for livestock. The first three plants require hydrogen as either primary or additional resource. All of the plants need electricity as input; some also require natural gas for heating or producing steam. Therefore, three energy streams are present at GLS: electricity, heat and hydrogen, and their synergies can create operational flexibility for the system. In here, we focused on electricity and hydrogen streams.

The source of the electricity stream at GLS is a renewable farm, comprising of 13 wind turbines and large number of solar panels capable of producing at peak 54 and 27 MW, respectively. The renewable farm output cannot be controlled or curtailed, and if the power was not consumed locally, it is sold upstream to an external network. The power could also be bought from there, in case of insufficient local renewable generation production. To buffer the intermittent renewable energy from the renewable farm a large-scale BESS with energy capacity of 1,6 MWh is installed at GLS.

The source of the hydrogen stream at GLS is an electrolyzer plant, where the water is decomposed by electrical current. Electrolyzer plant consists of multiple electrolyzer units with combined power consumption of 12 MW. Produced hydrogen is then stored in the hydrogen storage tank from where it is taken by HCPs. Hydrogen tank at GLS is presently being constructed and its actual capacity is unknown. We assumed the tank to be able to store 6 t (6000 kg) of hydrogen, so that it can supply 2 days of hydrogen demand.

2.2 *Energy management system*

2.2.1 Components

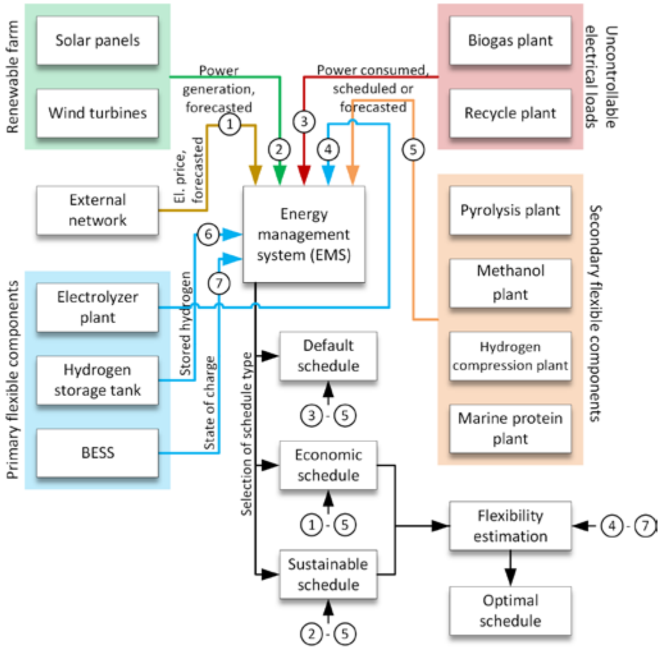

Fig 1 Proposed EMS architecture

Fig 1 shows proposed EMS architecture that encompasses all the components described in section 2.1. We grouped components into five categories based on the similarities in their behavior, operational characteristics and flexibility potential: renewable farm; external network; uncontrollable electrical loads; primary and secondary flexible components. The first two categories are electricity suppliers for GLS, the latter three are comprised of the electrical loads and energy storage units.

Biogas and recycle plants at GLS have nearly continuous operation at maximum power demand making them impossible to provide any form of flexibility to the system. Therefore, there are treated as uncontrollable electrical loads by an EMS.

Flexibility, understood here as an ability of the system components to change its energy consumption behavior, is provided by the primary and secondary flexible components. While the primary flexible components can provide flexibility to the system directly, the secondary flexible components allow to increase the flexibility from the primary ones. Primary flexible components are an electrolyzer plant, hydrogen storage tank and BESS. HCPs and marine protein plant providing P2X DR and conventional DR respectively, are the secondary flexible components; increase or decrease in HCPs' hydrogen consumption rates will affect how much extra hydrogen could be produced by an electrolyzer plant and stored in the hydrogen storage tank. Table 1 shows the information about operational characteristics of the plants that act as primary and secondary flexible components.

Table 1 Operational characteristics of the primary and secondary flexible components at GLS

Flexible component	**Working hours**	**Default schedule hourly consumption**	
		Electricity, [MW]	**Hydrogen, [kg]**
Electrolyzer plant	24	12,00	331
Pyrolysis plant	24	0,98	21
Methanol plant	24	0,70	60
Hydrogen compression plant	8	0,15	250
Marine protein plant	24	0,80	-

2.2.2 Functionality

Proposed EMS has following functionalities: day-ahead forecasting of renewable farm energy generation, industrial plants' power demand, and electricity market prices from external network; estimation of the system's flexibility potential; and optimal dispatch of primary and secondary flexible components. The paper focuses on the latter two functionalities, which are described below.

2.2.3 Operation

It is assumed that each industrial plant has its own day-ahead operational schedule based on its working shifts (8, 16 or 24 hours) and production goal. The main purpose of the EMS is to optimize all these schedules based on the common schedule type selected by the EMS operator. Three schedule types are proposed in this paper: default, economic and sustainable.

As a first step, EMS is collecting inputs from all the components indicated by colored arrows with circled numbers. Some of the inputs could only be forecasted (renewable farm, external network), while others could be received as day-ahead production schedules (industrial plants) or real-time values from sensors (energy storages).

Different inputs are needed by different schedules. For the default schedule inputs from 3 to 5 are used: EMS has to satisfy industrial plants power demands without optimizing them. In default schedule both hydrogen storage tank and BESS are kept for backup and charged to a certain level, but not active used. Economic and sustainable schedules utilize more inputs collected by EMS, if either of these schedule type was selected, an EMS will estimate the flexibility potential in the system by checking inputs from primary and secondary flexible components. After that an EMS will make the optimal schedule of the selected type – a collection of optimized schedules for each component – and ensure that all constraints are satisfied.

The details about how EMS optimizes individual production schedules for economic and sustainable schedule are given in the next section.

3. PROBLEM FORMULATION

3.1 Economic schedule

Economic schedule is achieved by setting an objective function to minimize system's operational cost shown in Eq 1, represented as costs of energy bought from external network and renewable farm, the energy increase/reduction provided by DR from secondary flexible components and the amount of hydrogen taken from the tank.

Here the cost of extracting hydrogen from the tank is calculated based on the average production cost of the hydrogen of the day it was stored in the tank. If the tank was charged at the day with low energy prices, it might be better to use that hydrogen than starting electrolyzer plant at certain hours. The cost of DR by itself is set to zero, because it is assumed that all flexible components provide it for the overall system's benefit. However, if the new operational schedule will cost more due to the higher energy prices, the difference between default and economic schedules should be paid out. The hydrogen compression plant consumes hydrogen by funneling it to its two trailers. If economic schedule proposes to do that at out-of-normal working hours, an extra cost is added to DR from that plant.

Following the economic objective function an EMS will optimize the day-ahead operational schedules of the primary and secondary flexible components to consume maximum power in the periods, when the electricity costs – either from external network or from renewable farm – are the lowest.

$$min \sum_{t=1}^{T} \Big(P_{ext,t} C_{ext,t} + \big(\sum_{w}^{WT} P_{w,t} C_{w,t} + \sum_{s}^{SP} P_{s,t} C_{s,t} \big) + \sum_{sfc}^{SFC} \Delta P_{sfc,t} C_{sfc,t} + \big(M_{H_2,t} - M_{H_2,t+1} \big) C_{H_2} \Big) \quad (1)$$

Objective function in Eq 1 is subject to constraints regarding energy balance (Eq 2), BESS SoC (Eq 3-5), hydrogen storage tank (Eq 6-8), marine protein plant (Eq 9), and HCPs (Eq 10).

The energy balance constraint is shown in Eq 2:

$$P_{ext,t} - P_{b,t} - P_{ele,t} + \sum_{w}^{WT} P_{w,t} + \sum_{s}^{SP} P_{s,t} + \sum_{l}^{L} P_{l,t} + \sum_{sfc}^{SFC} P_{sfc,t} = 0, \forall t \quad (2)$$

When BESS is charging, $P_{b,t}$ (and $I_{b,t}$) is positive. BESS SoC in Eq 3 is constrained by physical properties of the component and changes when BESS is charged or discharged [8].

$$SoC_t = SoC_{t-1} + \frac{\int_{t-1}^{t} I_b dt}{Q_b}, \forall t \quad (3)$$

$$SoC_0 = SoC_{initial} \quad (4)$$

$$SoC_{\min} \leq SoC_t \leq SoC_{max} \ , \forall t \quad (5)$$

The amount of hydrogen stored in the tank M_{H_2} is calculated as in [9]:

$$M_{H_2,t}, = M_{H_2,t-1}, + \int_{t-1}^{t} \Delta q_{H_2} dt \, , \forall t \quad (6)$$

$$M_{H_2,0} = M_{H_2,ini} \quad (7)$$

$$M_{H_2,min} \leq M_{H_2,t} \leq M_{H_2,max} \ , \forall t \quad (8)$$

Initial amount of hydrogen stored in the storage tank $M_{H_2,min}$ is set to ca 3 t (3000 kg), which corresponds to one day's consumption. Minimum amount in the tank is set to zero to gain more flexibility in the system.

Main condition for provision of conventional and P2X DR at GLS is that the total daily energy demand (either electrical power or hydrogen consumption in case of HCPs) for each plant should be kept constant to support regular operation. These constrains are formulated as:

$$\sum_{\mathrm{t}=1}^{\mathrm{T}} P_{pro,t}^{ds} = \sum_{\mathrm{t}=1}^{\mathrm{T}} P_{pro,t}^{rs} \quad (9)$$

$$\sum_{\mathrm{t}=1}^{\mathrm{T}} q_{H_2,i,t}^{ds} = \sum_{\mathrm{t}=1}^{\mathrm{T}} q_{H_2,i,t}^{rs}, \ \mathrm{i} \in \text{ HCPs} \quad (10)$$

To calculate electrical power-to-hydrogen ratio of an electrolyzer plant the logic described in [10, 11] was used.

3.2 Sustainable objective

If EMS is set to sustainable schedule, an objective is to produce hydrogen using only locally produced renewable energy. Objective function shown in Eq 11 maximizes total consumed power of electrolyzer, while constraint in Eq 12 restricts electrolyzer operation to only periods with sufficient renewable generation. It should be noted that the constrains in section 3.1, except for Eq 8, still apply. The lower limit in Eq 8 is changed to zero because in some cases when renewable energy is insufficient, the tank has to serve as a source of hydrogen supply. BESS can also be used to power electrolyzer, if it was charged with renewable energy beforehand. DR from secondary flexible components is used to shift their operational schedules so that more renewable energy could be "freed up" for the electrolyzer to use.

$$max \sum_{t=1}^{T} P_{ele,t} \quad (11)$$

$$P_{ele,t} \leq \max(\sum_{w}^{WT} P_{w,t} + \sum_{s}^{SP} P_{s,t} + P_{b,t} - \sum_{sfc}^{SFC} P_{sfc,t} - \sum_{l}^{L} P_{l,t}), \forall t \quad (12)$$

4. RESULTS

Results of the default (**Def**) and proposed by EMS economic (**Ec**) and sustainable (**Su**) schedules are summarized in Table 2 for four scenarios: **S1** – low renewable generation and low electricity prices; **S2** – low renewables/high prices; **S3** – high renewables/low prices and **S4** – high renewables/high prices. Scenarios are built using weather and electricity price data from [12, 13].

Table 2 Results from EMS following different schedules in four scenarios

	S1			S2			S3			S4		
	Def	**Ec**	**Su**	**Def**	**Ec**	**Su**	**Def**	**Ec**	**Su**	**Def**	**Ec**	**Su**
Total hydrogen production, [t]	4,20	4,32	2,00	4,20	0,94	2,00	4,20	4,32	6,80	4,20	0,94	6,80
Share of green hydrogen, [%]	50,13	39,44	100	50,13	0	100	100	100	100	100	100	100
Total cost of hydrogen, [k€]	3,23	3,15	1,20	3,94	1,13	1,20	2,53	2,60	4,10	2,53	0,57	4,10
Average cost of hydrogen, [€/kg]	0,77	0,73	0,60	0,94	1,20	0,60	0,60	0,60	0,60	0,60	0,60	0,60
Change in hydrogen tank, [t]	0	0,40	-1,86	0	-2,98	-1,86	0	0,40	2,93	0	-2,91	2,93
Total operational costs, [k€]	12,09	6,99	7,50	14,76	7,57	8,01	0,02	-5,08	-4,86	-6,85	-14,04	-12,16

Final results are obtained using mixed-integer linear programming with coin-or-branch and cut solver to optimize Eq 1 and 11.

Switching EMS from providing default schedule to either economic or sustainable schedules results in reducing system's total operational costs. When they are negative – system receives extra profits by selling renewable energy to the external network. For each scenario economic schedule provides the lowest operational costs (highlighted in light blue in Table 2).

In every schedule, some amount of green hydrogen is produced, however in sustainable schedule its share is always 100% (green color in Table 2). During days with insufficient renewable generation, hydrogen from the storage tank is used to cover the rest of the HCPs demand (S1-S2) – indicated by the negative value of the change in hydrogen tank. Hydrogen storage tank would be recharged in days like S3-S4 (positive value).

When switching from economic to sustainable schedule in S1 and S2 the total operational costs would increase by ca 7,3% and 5,8% respectively. For S3 and S4, 100% green hydrogen is already produced by following an economic schedule and therefore no extra cost is incurred. However, this is only possible if the hydrogen tank was previously charged with green hydrogen, as the system in economic schedule does not produce enough hydrogen to cover its daily demand. Therefore, in some days like S3 and S4, EMS will operate the system in sustainable schedule to be able to charge the hydrogen storage tank. The total operational costs from choosing sustainable schedule over economic one in S3 and S4 would increase by ca 4,2% and 13,4% respectively.

Fig 2 show an example of how electrolyzer plant would be operated according to default, economic and sustainable day-ahead schedules in S3. It could be seen that with high amount of renewable generation electrolyzer plant run continuously on full power in sustainable schedule as opposed to the middle-maximum-middle power operation in default schedule and maximum-minimum power in economic schedule. In Fig 3-4 the day-ahead operations of BESS and marine protein plants, and HCPS are presented in default and sustainable schedules to illustrate, when and how DR and P2X DR are activated. Instead of default constant hydrogen/power consumption HCPs and marine protein

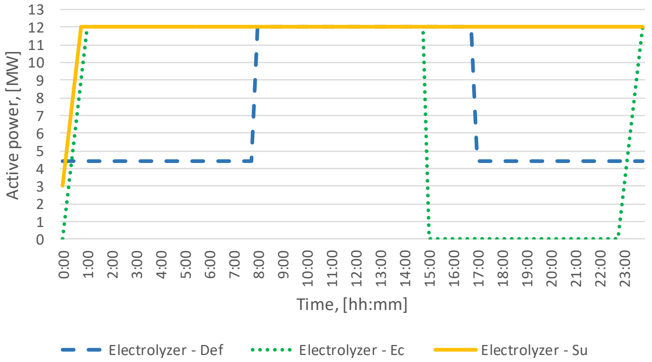

Fig 2 Electrolyzer plant operation in Def, Ec and Su schedule

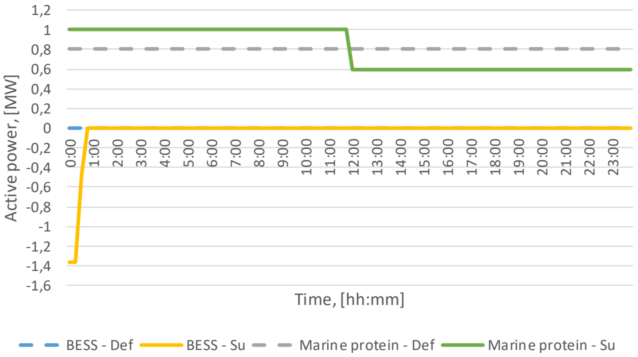

Fig 3 BESS and protein plant operation in Def and Su schedule

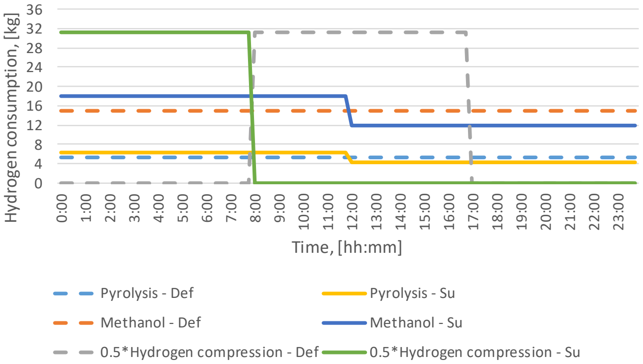

Fig 4 Pyrolysis, methanol and hydrogen compression plants operation in Def and Su schedule

plant's operation is modified to better follow the renewable generation with sustainable schedule. The total hydrogen/power consumption of secondary flexible components remains the same in both schedules. From Fig 3 it could be concluded that BESS capacity is not sufficient to play a significant role as flexible component.

Presented results demonstrate the capabilities of the proposed EMS to achieve both economic and sustainable benefits.

5. CONCLUSIONS AND FUTURE WORK

In this paper we propose an EMS architecture that combines hydrogen production with renewable generation. EMS is based on the components of GLS and changes their operation from following default schedule to either economic or sustainable schedules. These schedules allow the system to reduce its total operational costs and/or produce 100% green hydrogen, while satisfying all production goals of individual plants at the same time. In some considered scenarios, EMS at GLS is capable of producing a day-ahead economic schedule with completely sustainable hydrogen production. When the system is switched from following economic schedule, which could be a case of today, to a sustainable schedule – potential future goal – the operational costs would increase by ca 4,2%-13,4% depending on the weather conditions and the electricity prices in that day. The flexibility is provided by conventional DR and a novel P2X DR from HCPs; this shows how important it is to use the synergies between different energy streams in obtaining flexibility.

Future research on this topic will include more advanced models for primary and secondary flexible components. In addition, deeper investigation of the P2X DR potential is required together with the estimation of the annual benefits that system gets from following a specific schedule. Finally, components' optimal dispatch could be improved by using more advanced optimization methods.

REFERENCE

[1] Ørsted and partners secure funding for renewable hydrogen project. https://orsted.com. (Online)

[2] Leading Danish companies join forces on an ambitious sustainable fuel project. https://www.maersk.co. (Online)

[3] Germany bets on green hydrogen in quest for climate neutrality. https://www.pv-magazine.com. (Online)

[4] Vivas, F. J., De las Heras, A., Segura, F., & Andújar, J. M. A review of energy management strategies for renewable hybrid energy systems with hydrogen backup. Renewable and Sustainable Energy Reviews 2018; 82: 126-155.

[5] Rullo, P., Braccia, L., Luppi, P., Zumoffen, D., & Feroldi, D. Integration of sizing and energy management based on economic predictive control for standalone hybrid renewable energy systems. Renewable Energy 2019; 140:436-451.

[6] GreenLab Skive. https://www.greenlabskive.dk/. (Online)

[7] Symbiosis center Denmark. https://symbiosecenter.dk/en/. (Online)

[8] Chan H. L. A new battery model for use with battery energy storage systems and electric vehicles power systems. 2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings – IEEE 2000; 1:470-475.

[9] Castaneda, M., Cano, A., Jurado, F., Sánchez, H., & Fernández, L. M. Sizing optimization, dynamic modeling and energy management strategies of a stand-alone PV/hydrogen/battery-based hybrid system. International journal of hydrogen energy 2013; 38(10): 3830-3845.

[10] Olivier, P., Bourasseau, C., & Bouamama, P. B. Low-temperature electrolysis system modelling: A review. Renewable and Sustainable Energy Reviews 2017; 78:280-300.

[11] Ulleberg, Ø. Modeling of advanced alkaline electrolyzers: a system simulation approach. International journal of hydrogen energy 2003; 28(1):21-33.

[12] The European Commission's science and knowledge service. https://ec.europa.eu/jrc/en. (Online)

[13] Nord Pool. https://www.nordpoolgroup.com/. (Online)