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Optimal Energy Flow of Integrated Energy Systems with Hydrogen Economy Considerations

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Abstract **- This paper investigates the formulation of a general optimal energy flow (OEF) problem for integrated energy systems, paying particular attention to "hydrogen economy" issues, i.e. production, distribution and utilization of hydrogen, as well as considering the impact of energy storage devices. Based on the concept of energy hubs, the optimal conversion and transmission of multiple energy sources and energy carriers, in particular natural gas, electricity, district heat and hydrogen, considering energy storage devices are discussed. A 3 energy-hub system with electricity, gas, heat and hydrogen production, distribution, demand and storage capabilities is used to illustrate some of the proposed concepts and analysis techniques. The results illustrate some of the advantages of combining different energy sources and carriers, particularly if hydrogen is considered as an integral part of the energy system, given its storage characteristics.**

I. INTRODUCTION

Due to economic and environmental considerations, as well as flexibility in power production, the use of distributed generation (DG) is spreading throughout the world. In systems with DG, there exist different energy flow problems associated with different energy sources and carriers, such as natural gas, electricity, heat, and hydrogen, which are tightly coupled due to the interactions among these various sources and carriers. For example, a microturbine being fed from natural gas can produce electricity and heat simultaneously, and an electrolyzer being fed from the electric network can satisfy both hydrogen demand and part of the heat demand. Hence, an integrated overview of energy systems is needed to properly study energy flows, conversion and possible storage of the different energy carriers [1]-[3].

To facilitate the study of multiple energy-carrier flows and their interactions, the concept of "energy hubs" has been proposed [4]-[8]. An energy hub is an interface between energy loads (e.g. electricity, heat, compressed air, and hydrogen) and primary energy sources and carriers (e.g. electricity, natural gas, district heat, and hydrogen), and can be studied as a comprehensive node of an integrated energy system with different inputs and outputs and various converters, such as transformers, microturbines, electrolyzers and fuel cells, and storage devices for gas, heat and hydrogen. Since different converters inside the hub have different characteristics, with particular costs associated with different energy sources and related energy carriers, an optimal dispatch problem can be formulated for the hub and associated energy system. The solution of this problem specifies the optimal contribution of each energy source and energy carrier to meet the required demand at minimum costs. If steady-state energy flow equations together with network constraints for each of the individual networks such as electricity and gas are considered, then a general optimal energy flow (OEF) problem for the integrated energy system can be formulated; this is the analysis approach used in this paper.

In the last few years, the concept of a "hydrogen economy" has gained much attention both in industry and academia. Hydrogen as an energy carrier can link or interface multiple energy resources like fossil fuels, nuclear, and renewables for multiple end-uses; this has led to the development of the hydrogen economy concept, which concentrates on the study of the economic aspects associated with the production, distribution and utilization of hydrogen in energy systems. In this respect, important issues in the hydrogen economy are the costs of production, storage, and delivery to customers of hydrogen as an energy carrier. There are many issues and debates with regard to the hydrogen economy, with strong advocates and opponents [9]-[12]. Although at the present state of technological development, there are a variety of concerns regarding the production, distribution, storage and use of hydrogen, many of these concerns should be addressed with the course of time [13], as proper solutions are developed to solve the challenges that are currently being faced with regard to the use of hydrogen as an energy carrier in integrated energy systems. From the power grid point of view, the use of hydrogen as an energy carrier is appealing, given its storage characteristics. In particular, the economics of production, storage and utilization of hydrogen have become relevant in the context of competitive electricity markets, given the significant price differences between peak and low price hours (which may or may not necessarily coincide with peak and low demand hours) [14], and considering that classical generation plants are most efficient when operating at rated load levels. Furthermore, if one considers typical technical problems in the electric transmission system during the normal

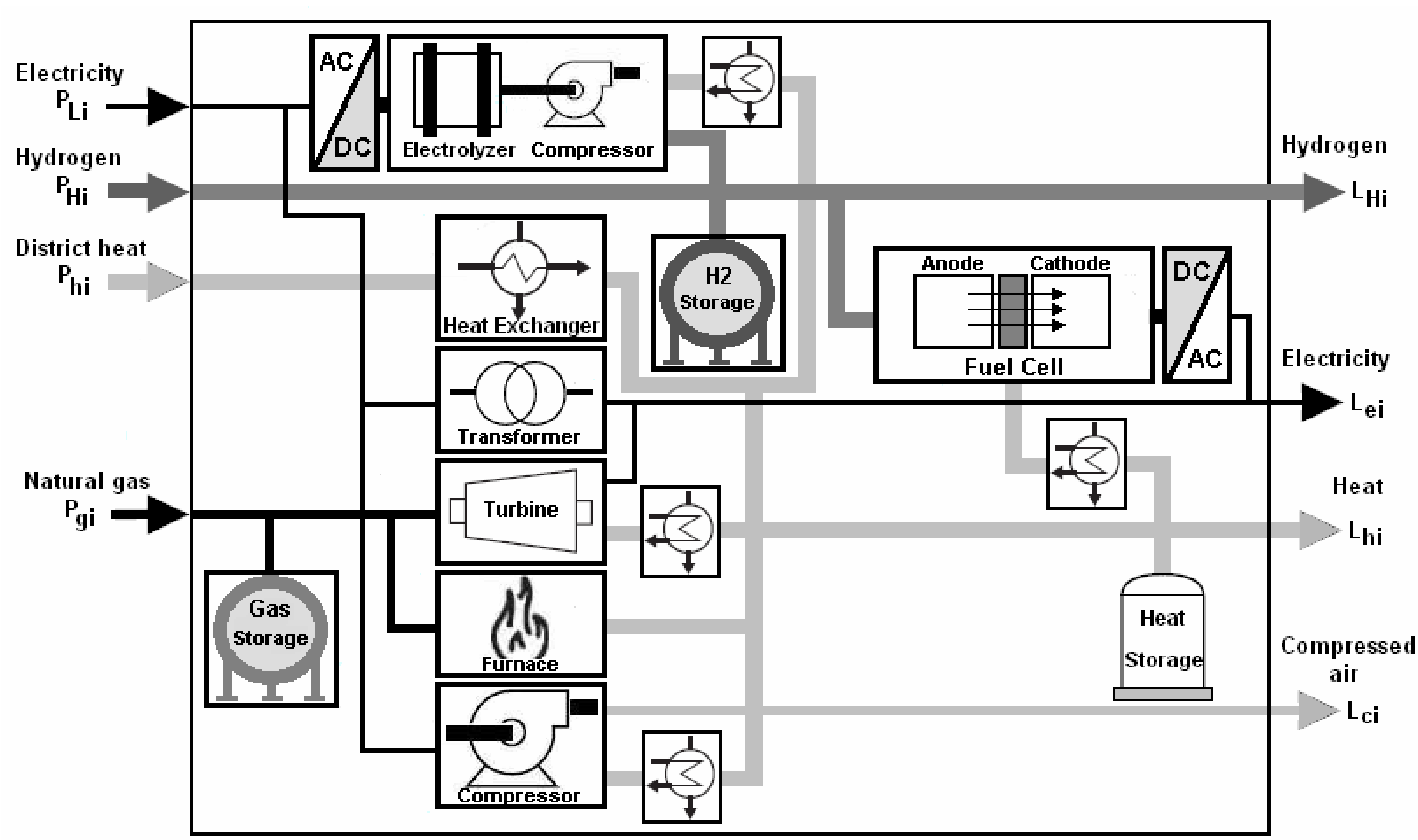

Fig. 1: Configuration of a comprehensive energy hub.

operation of a power grid, the use of hydrogen as an energy carrier to increase the efficiency and reliability of the grid becomes certainly an attractive option. Finally, if the various advantages of the usage of hydrogen in transportation applications are factored in, the importance of studying the production, distribution and utilization of hydrogen in association with the electricity gird, while considering other associated energy carriers, becomes evident. In view of all these issues, a hydrogen network that includes converters (electrolyzer and fuel cell), storage, and demand are studied in this paper as part of an integrated energy system with electricity, gas and heat production and demand. Hence, this paper deals with the OEF of integrated energy systems following the techniques proposed in [4]-[8], paying particular attention to the following two issues: production, distribution and utilization of hydrogen; and the consideration of storage devices within the energy hub.

The rest of the paper is structured as follows: In Section II, the optimization model of an integrated energy system considering hydrogen production, storage, and demand are presented. In Section III, a 3-hub energy system comprised of electricity, hydrogen, district heat, and natural gas networks is described, and the results of applying the proposed OEF analysis are presented and discussed. Finally, Section V highlights the main contributions of this paper.

II. INTEGRATED ENERGY SYSTEM OPTIMIZATION MODEL

The nodes of an integrated energy system that includes hydrogen, district heat, natural gas, and electricity networks may be represented by energy hubs. These hubs, as illustrated in Fig. 1, could be comprised of transformers; compressors; microturbines; furnaces; rectifiers and electrolyzers; fuel cells and inverters; heat exchangers; and various energy storage devices. Taking into account the networks' constraints and for given energy demands in a certain time period, the optimal contributions of each network, converter and storage device inside the hub can be analyzed with the objective of minimizing total energy costs. Hence, an optimization model for these types of studies can be developed, as discussed in this section.

A. Objective Function

The objective function to be minimized is the total energy cost in the integrated energy system for a given time period. This may be expressed as:

$$TC = \sum_{s \in \Omega} \sum_{t=1}^{T} \left(a_s^t + b_s^t P_s^t + c_s^t P_s^{t\,2} \right) \tag{1}$$

Where Ω is the set of all energy suppliers in the integrated energy system; P_s^t is the corresponding supplied power at time *t;* and a_s^t, b_s^t, and c_s^t are the corresponding cost coefficients. In this study, P_s^t includes power supplied by electricity (*e*), hydrogen (H_2), district heat (*h*), and natural gas (*g*) networks.

B. Constraints [4]-[8]

1. Energy flow equations: These equations correspond to the "flow" equations of the electricity, hydrogen, district heat, and gas networks:

$$\left.\begin{aligned} &\mathbf{G}_\alpha^t = 0 \\ &\underline{\mathbf{F}}_\alpha \le \mathbf{F}_\alpha^t \le \overline{\mathbf{F}}_\alpha \end{aligned}\right\} \forall \alpha \in \mathcal{E} \wedge t \in \mathcal{T} \tag{2}$$

where $\mathbf{G}_\alpha$ is the set of network equations for the α energy source or energy carrier (e.g. the gas network flow equations [7]); $\mathbf{F}_\alpha$ is the set of power flow variables for the α energy source or energy carrier (e.g. the set of H_2 network power flow variables), which are bounded by minimum and maximum limits $\underline{\mathbf{F}}_\alpha$ and $\overline{\mathbf{F}}_\alpha$, respectively; $\mathcal{E} = \{e, g, H_2, h\}$; and $\mathcal{T} = \{1, 2, ..., T\}$.

2. Electricity network limits: These limits correspond to bus voltage magnitudes $|V|$, active powers P_G, reactive powers Q_G, and apparent powers S_G of generators in the electricity network. These limits can mathematically be expressed as follows:

$$\left.\begin{aligned} &\underline{V}_m \le \left|V_m^t\right| \le \overline{V}_m \\ &\underline{P}_{G_m} \le P_{G_m}^t \le \overline{P}_{G_m} \\ &\underline{Q}_{G_m} \le Q_{G_m}^t \le \overline{Q}_{G_m} \\ &\underline{S}_{G_m} \le S_{G_m}^t \le \overline{S}_{G_m} \end{aligned}\right\} \forall m \in \mathcal{M} \wedge t \in \mathcal{T} \tag{3}$$

where $\mathcal{M}$ is the set of nodes (energy hubs).

3. Gas, hydrogen, and heat networks limits: These correspond to the limits on nodal pressures and compression ratios of compressors in all the gaseous networks, since it is assumed here that gas, hydrogen, and heat are transported using somewhat similar transportation mechanisms. Thus:

$$\left.\begin{aligned} &\underline{\pi}_{mr} \le \pi_{mr}^t \le \overline{\pi}_{mr} \\ &\underline{\pi}_{mc} \le \frac{\pi_{mr}^t}{\pi_{cr}^t} \le \overline{\pi}_{mc} \end{aligned}\right\} \begin{aligned} &\forall m \in \mathcal{M} \wedge r \in \mathcal{G} \\ &\forall t \in \mathcal{T} \wedge c \in \mathcal{C} \end{aligned} \tag{4}$$

where π_{mr} is the discharge pressure; π_{mc} is the suction pressure of compressor *c*, with $\underline{\pi}_{mc}$ and $\overline{\pi}_{mc}$ minimum and maximum limits, respectively; $\mathcal{G} = \{g, H_2, h\}$; and $\mathcal{C}$ is the set of compressors (not all branches have compressors).

4. Hub energy flow equations: These equations represent the balance between demands and input powers in the hubs and are expressed as follows:

$$\mathbf{L}_m^t - \mathbf{C}_m^t \mathbf{P}_m^t + \mathbf{M}_m^{\mathbf{eq}\,t} = \mathbf{0} \quad \forall m \in \mathcal{M} \wedge t \in \mathcal{T} \tag{5}$$

where $\mathbf{L}_m$ is the vector of energy demands; $\mathbf{C}_m$ is the converter coupling matrix relating input and output hub powers (e.g. [8]); and $\mathbf{M}_m^{\mathbf{eq}}$ is the set of equivalent storage power exchange, which is defined as:

$$\mathbf{M}_m^{\mathbf{eq}\,t} = \mathbf{S}_m^t \frac{\mathbf{dE}_m^t}{\mathbf{dt}} = \mathbf{S}_m^t \left[\mathbf{E}_m^t - \mathbf{E}_m^{(t-1)} + \mathbf{E}_m^{stb} \right] \tag{6}$$
$$\forall m \in \mathcal{M} \wedge t \in \mathcal{T}$$

where $\mathbf{E}_m^t$ is the vector of stored energy in hub m at the end of time period t; $\mathbf{E}_m^{stb}$ represents the standby energy losses in hub m for all time periods; and $\mathbf{S}$ is the storage coupling matrix, which describes how changes of the storage energies affect the hub output flows [8].

5. Dispatching factor limits: These limits can be stated as:

$$0 \le \nu_{m\alpha k}^t \le 1 \;\; \forall m \in \mathcal{M} \wedge \alpha \in \mathcal{E} \wedge k \in \mathcal{K} \qquad (7)$$

where the dispatching factors $\nu_{m\alpha k}$ define the split of power input to hub m of energy carrier α at converter k; and $\mathcal{K}$ is the set of hub converters, i.e. electrolyzers, fuel cells, transformers, and gas turbines.

6. Hub converter limits: These limits are defined as follows:

$$\begin{aligned} & 0 \le \eta_{m\alpha k} \nu_{m\alpha k}^t P_{m\alpha}^t \le \overline{P}_{m\alpha k} \\ & \forall m \in \mathcal{M} \wedge \alpha \in \mathcal{E} \wedge k \in \mathcal{K} \end{aligned} \qquad (8)$$

where $\eta_{m\alpha k}$ is the efficiency of the converter k for hub m and energy carrier α; and $P_{m\alpha}$ is the input power to converter k, with the converter output power being limited by $\overline{P}_{m\alpha k}$.

7. Energy storage and power exchange limits: These are represented by:

$$\left.\begin{aligned} \underline{\mathbf{E}}_m \le \mathbf{E}_m^t \le \overline{\mathbf{E}}_m \\ \underline{Q}_{m\sigma} \le Q_{m\sigma}^t \le \overline{Q}_{m\sigma} \\ \underline{M}_{m\gamma} \le M_{m\gamma}^t \le \overline{M}_{m\gamma} \end{aligned}\right\} \forall m \in \mathcal{M} \wedge \sigma, \gamma \in \mathcal{S} \qquad (9)$$

where $Q_{m\sigma}^t$ is the exchanged power of the storage device σ at time period t at the input side of the hub m, which is bounded by minimum and maximum limits $\underline{Q}_{m\sigma}$ and $\overline{Q}_{m\sigma}$, respectively; $M_{m\gamma}^t$ is the exchanged power of the storage device γ at time period t at the output side of the hub m, which is bounded by minimum and maximum limits $\underline{M}_{m\gamma}$ and $\overline{M}_{m\gamma}$, respectively; and $\mathcal{S}$ is the type of energy storage devices inside the hub, i.e. $\mathcal{S} = \{g, H_2, h\}$. It is to be noted that the time derivative of stored energy is the power exchange; however, the charging or discharging efficiencies, i.e. e^+, e_-, respectively, should be taken into account. For example, if the gas storage in Fig. 1 is under charging process, then the power exchange and stored energy of this storage device in Hub 1 are related by $Q_{1g} = \frac{1}{e_g^+}\frac{dE_{1g}}{dt}$.

8. Sustainability constraints: These represent the values of stored energy at the end of the study period T, which have to be equal to the corresponding initial values for the storage devices. Thus:

$$\mathbf{E}_m^0 = \mathbf{E}_m^T \;\; \forall m \in \mathcal{M} \qquad (10)$$

III. CASE STUDY

A. Sample System

The 3-hub integrated energy system shown in Fig. 2, which includes hydrogen, district heat, natural gas, and electricity networks, is investigated here for a 24-hour time period. The electricity network in Fig. 2 is assumed to be supplied by generators G_1 (slack generator), which feeds Hub 1, and G_2, which feeds Hub 2. The gas network is fed by a single source N of known-pressure feeding Hub 1, and two compressors, one connected between Hubs 1 and 2, and the other one connected between Hubs 1 and 3. It is also assumed that there are bounded local sources of hydrogen and heat at the input side of each hub.

As per (1), the cost function for each individual energy source or energy carrier, i.e. G_1, G_2, N, and the local H_2 and h sources, has three components. To provide a cost comparison, the assumed values of b of the cost function for all the sources are depicted in Fig. 3. Observe that hydrogen, district heat, and natural gas have all fixed prices, and the tariff system for electricity includes two different prices: one from 23 to 6 hours, and the other one for 7 to 22 hours. The required load powers are shown in Fig. 4. The electricity demand is assumed as a typical load on a summer day. The heat demand is distributed in three time frames, i.e. 4-9, 12-15, and 18-22 hours. The demand for compressed air starts at hour 7 and ends at hour 18. There are 4 hours of hydrogen demand (refuelling the cars); 2 hours in the morning (7-8), and 2 hours in the evening (19-20). The rest of the data is provided in the Appendix, for the interested reader. Some of the parameters values used here where chosen based on realistic figures.

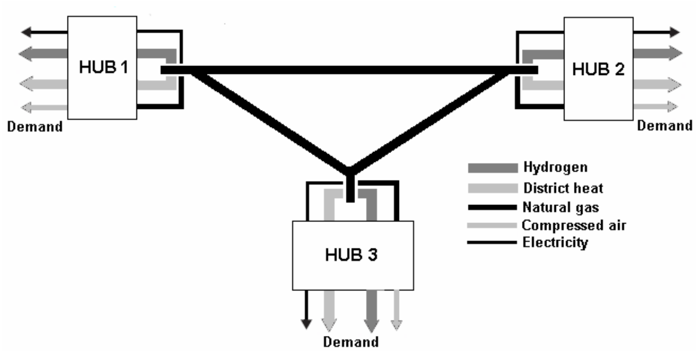

Fig. 2: Configuration of the sample integrated energy system.

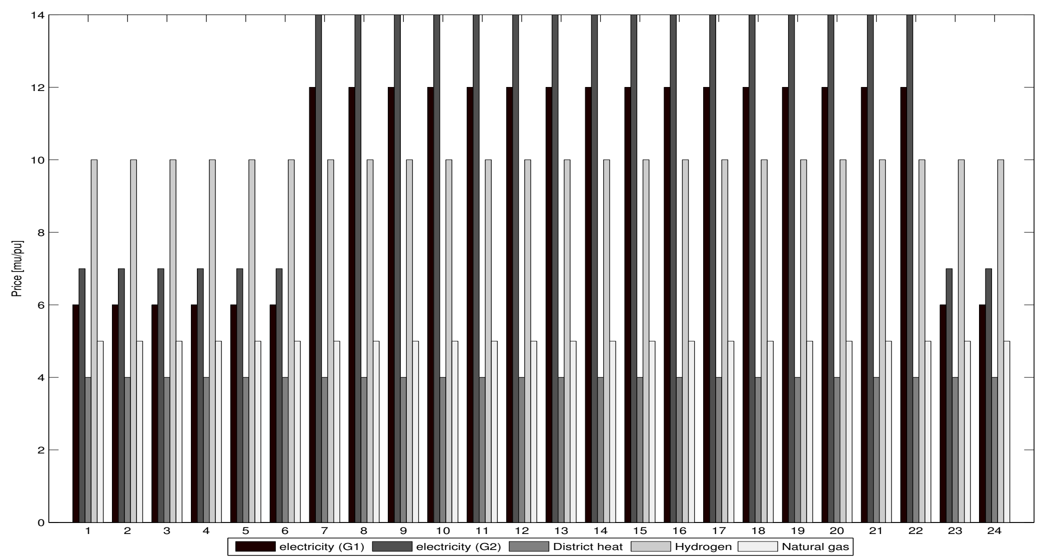

Fig. 3: Hourly energy costs in monetary units (mu) per pu power.

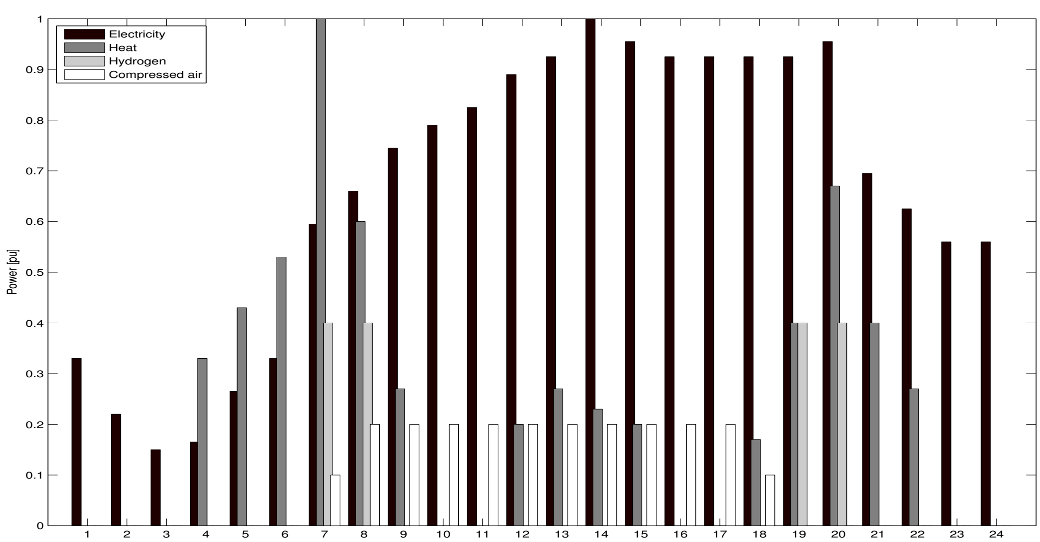

Fig. 4: Hourly demand powers.

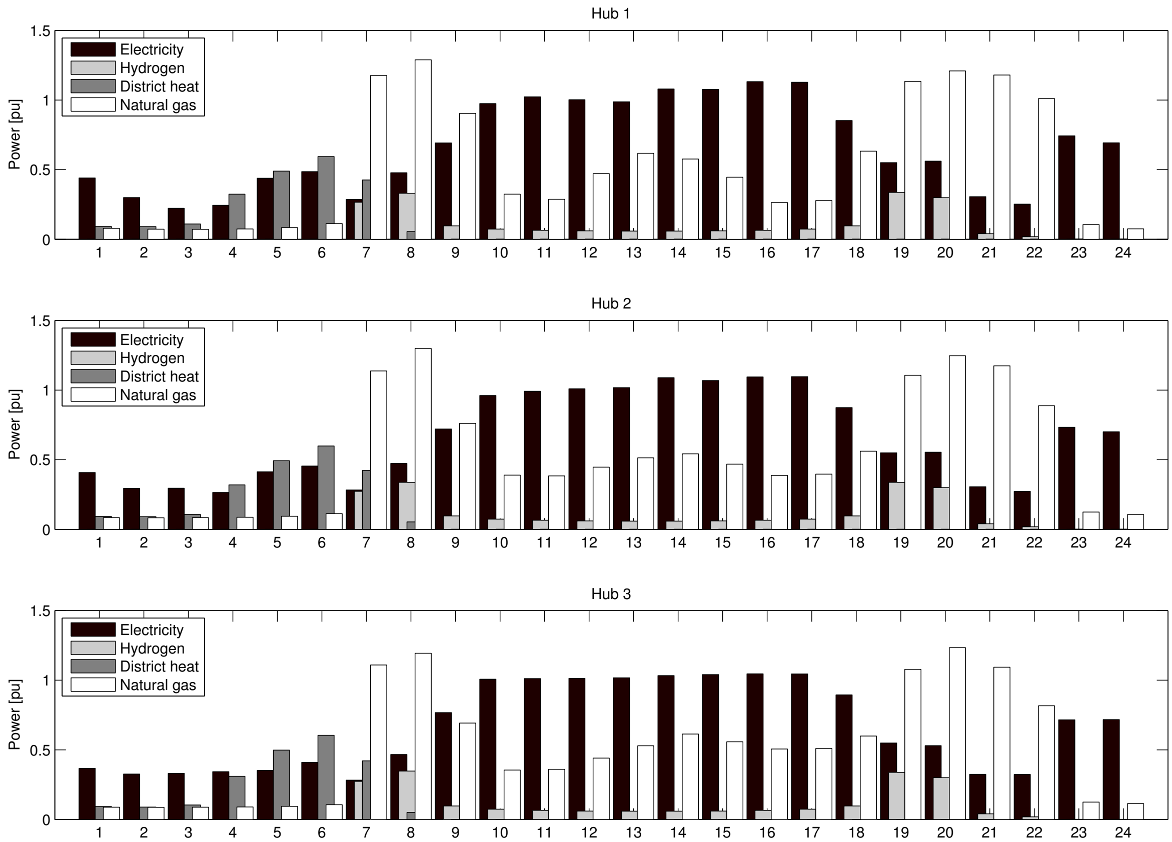

Fig. 5: Hourly input powers to hubs.

B. Results and Discussions

Based on the assumed demand powers for 24 hours, the optimal values of hubs' input powers as well as storage energy were found solving the optimization model proposed in Section II with the help of AMPL [15] and KNITRO [16], and the results are shown in Fig. 5 and 6. Observe in Fig. 5 that, except for some minor differences at hours 4 and 9 for Hub 3 and some minor shifts in peak powers, the input powers follow somewhat similar patterns in all three hubs. Notice as well that due to the interaction of different devices inside each hub and in particular the storage devices, the pattern of electricity input is not similar to electricity demand, in particular during hours 6-8 and 22-24. It is interesting to note that, although there is no heat demand during the first three hours (1-3), there is heat and gas consumption by the hub due to the gas and heat storage devices.

Observe in Fig. 6, that during hours 1-3, the consumed heat and gas are stored in the corresponding storage devices for use during heat peak hours (mainly hours 7 and 8); also notice that during the first three hours, the content of hydrogen storage increases as well. This shows that even with no hydrogen demand, some part of the input electricity is consumed by the electrolyzer for hydrogen production, hence benefiting from the cheap electricity (off-peak price); the same happens at the start of the next off-peak hours (hour 23). Although the hydrogen demand is limited to hours 7-8 and 19-20, observe in Fig. 5 that there is hydrogen consumption by all three hubs during hours 9-18 as well; this consumed hydrogen must be stored for use during the next hydrogen demand hours (19-20). This observation is confirmed in Fig. 6, as there is gradual increase of hydrogen storage in all three hubs during hours 9-18.

Notice in Fig. 6 that the charging and discharging processes of heat and hydrogen storage devices follow a somewhat similar pattern to the corresponding energy demand. This means that charging occurs when there are low demands of heat and hydrogen, and discharging occurs at high demand hours of heat and hydrogen; however, during hours 4-6, when there is relatively high demand of heat, the gas storage increases. This makes sense since there is a cheaper energy vector (district heat) available to satisfy the heat demand during these hours, and thus

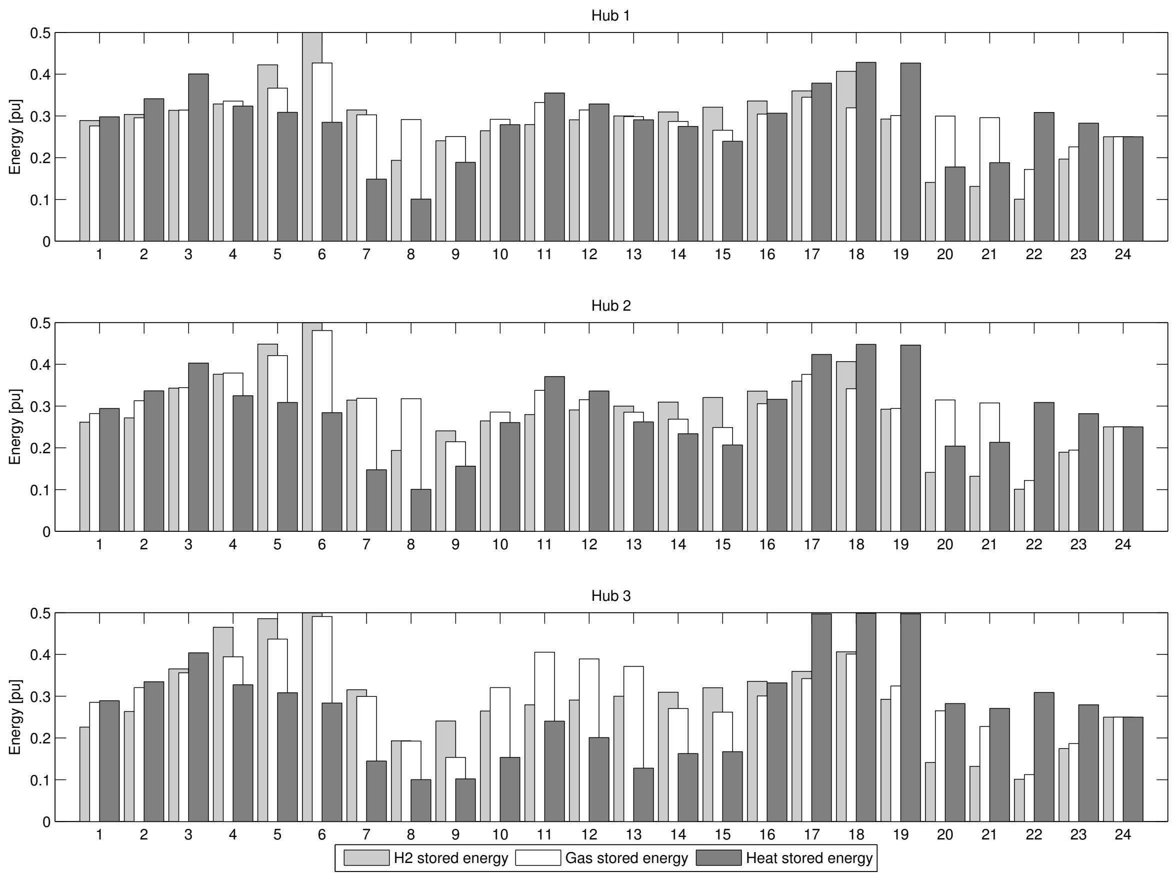

Fig. 6: Hourly stored energy.

there is no need for gas conversion to heat by turbine or furnace, with the consumed gas being stored for use during hours 7-8, when there is higher demand of heat. It is also worth noting that during hours 23-24, when the only demand is electricity and there is no heat demand, the consumed gas can be stored, and since there is relatively cheap electricity available, hydrogen can be produced by the electrolyzer and stored, thus yielding an increase of gas and hydrogen storage contents. However, the same does not happen for heat storage. Thus, observe that due to availability of cheap district heat, there should be some heat consumption by the hub, which would result in an increase in heat storage; however, this does not happen because of the sustainability constraint.

The contribution of different devices to the supply of electricity demand can be analyzed with the help of Fig. 7 which shows the contribution to the demand from fuel cells, transformers, and gas turbines. Observe that during the first 6 hours and hours 23-24, all the electricity demand is covered by the transformers as there is relatively cheap electricity available with the contribution of fuel cells and gas turbines being negligible. The maximum contribution of the gas turbine at this time interval (1-6) is at hour 3 with 0.33% share in Hub 3. Although at hours 10-11 and 16-17 (on-peak electricity price interval) there is a cheaper energy vector available (hydrogen), most of the electricity demand is still covered by transformers, which can only be explained in terms of the low-efficiency energy pathway through fuel cell (98% for a transformer compared to 55% for a fuel cell); the difference in energy prices is not large enough to justify contributions from the fuel cells, in view of their efficiency. During hours 7-8 and 21-22 (on-peak electricity price interval) the share of gas turbine for covering electricity demand is dominant, which is to be expected since gas is significantly cheaper than electricity.

The contribution of different devices in supplying the heat demand is depicted in Fig. 8; as the contribution of fuel cells and furnaces is so small, they are not shown in this figure (e.g. the maximum contribution of furnaces is at hour 18 in Hub 1, with 0.37% share, and for fuel cells is at hour 8 in Hub 3, with 1.39%.

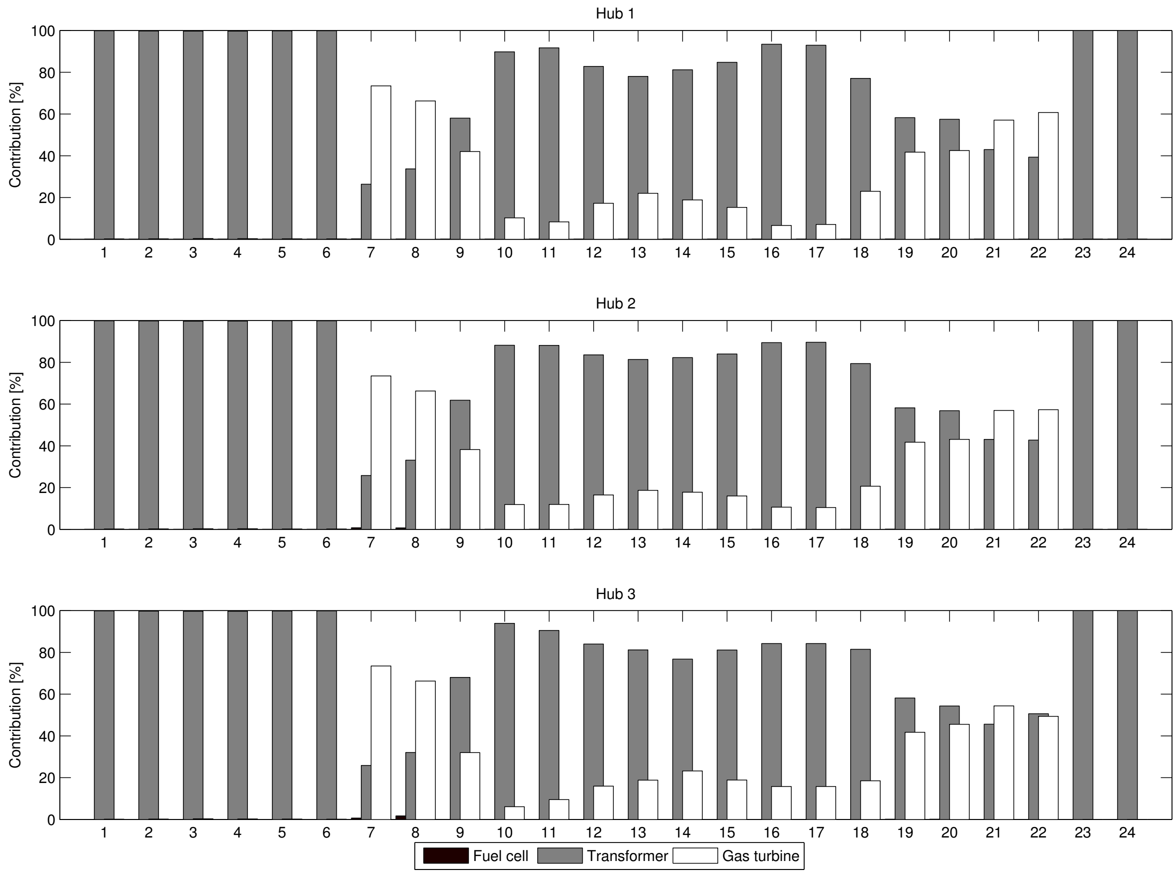

Fig. 7: Percent of contributions to electricity demand.

Note that the main supplier of heat is district heat (through heat exchangers) because of its low price. Nevertheless, electrolyzers and heat exchangers do contribute; thus, for example, the maximum contribution of the electrolyzers is observed at hour 4 in Hub 3, with a 7.12% share. It is interesting to note that the operation of electrolyzers is confined to hours when there is cheap electricity available, i.e. hours 4-6. Heat storage acts as an energy source, discharging at hour 4 with an 8.2% contribution, and acts as an energy sink, charging at hours 5 and 6, with -8.13% (= -.035 pu) and -4.95% (= -.026 pu) contributions, respectively. This might seem to be in contradiction with what is observed in Fig. 6, as the value of heat storage decreases during hours 4-6; however, one should consider that there is an assumed 0.05 pu constant standby loss at each hour, which is why the value of heat storage decreases in spite of being charged. Another important point is the dominant contribution of gas turbine during hours 12-15 and 18-22 in all three hubs, in spite of the cheap district heat being available. The reason for this is that these two time intervals coincide with two peak electricity demands, when the gas turbine supplies for this demand, as previously explained; therefore, since gas turbine also generate significant heat, and together with the output heat of compressors and heat storage devices, these are sufficient to cover the heat demand.

The contribution of the hydrogen network, electrolyzers, and hydrogen storage devices for covering the hydrogen demand is shown in Fig. 9. Observe that there is practically no contribution of electrolyzers to the hydrogen demand, which is due to the fact that hydrogen demand hours coincide with on-peak electricity prices, and therefore there is no need for hydrogen production through the expensive energy pathway provided by the electrolyzers. It is also worth noting that the operation of electrolyzers is not limited to the hydrogen demand hours (7-8 and 19-20), due to the presence of hydrogen storage devices. Thus, during the hours with no hydrogen demand, the generated hydrogen by the electrolyzers is stored, and the heat which is produced can be used to cover part of the heat load or be stored.

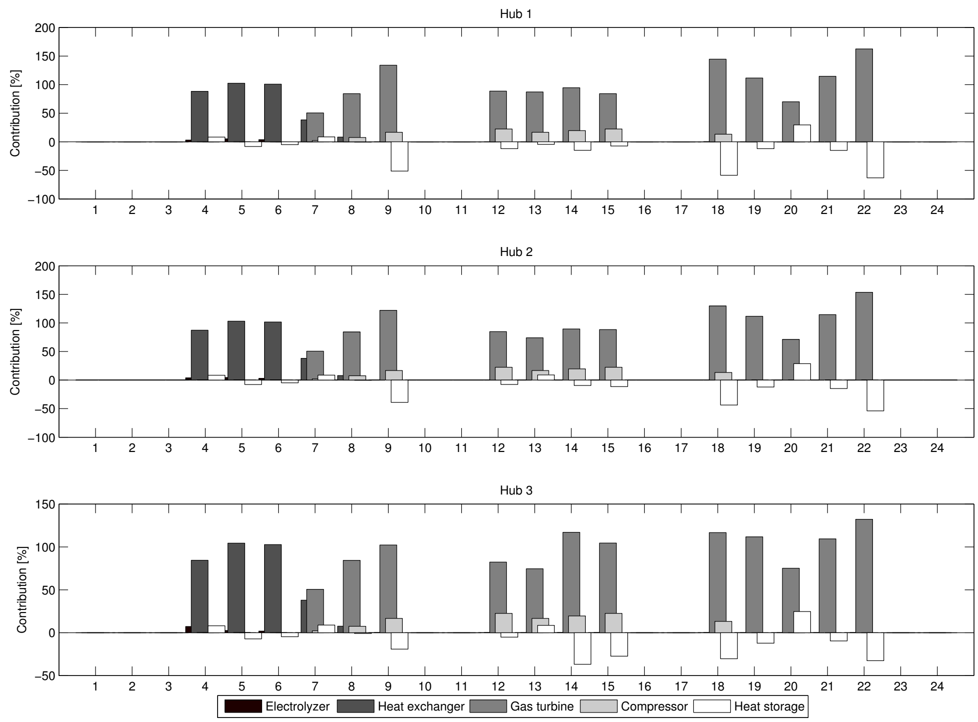

Fig. 8: Percent of contributions to heat demand.

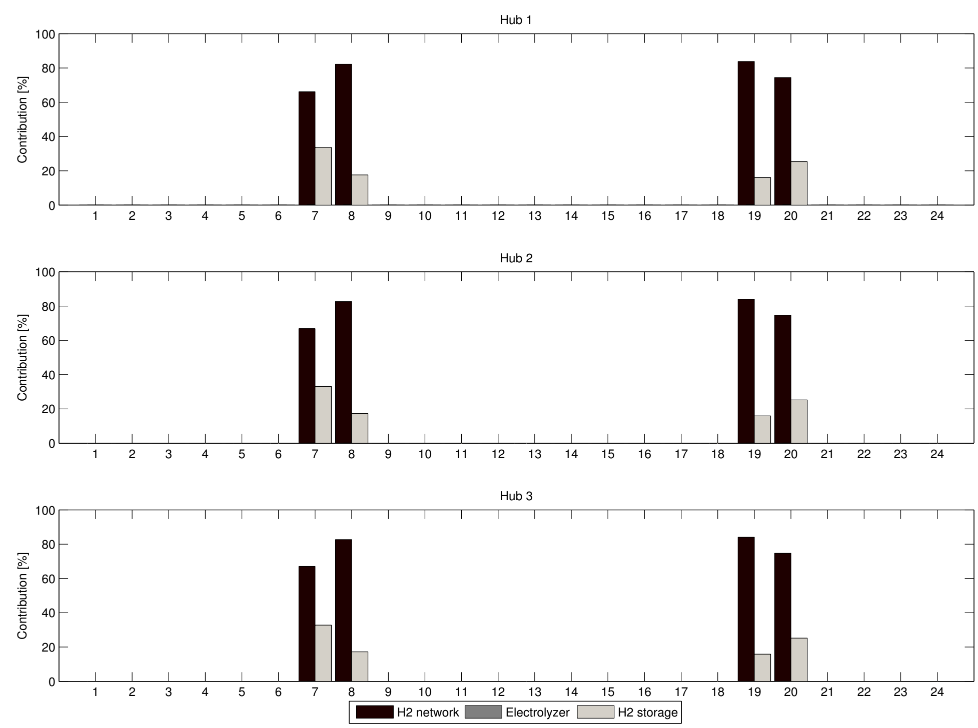

Fig. 9: Percent of contributions to hydrogen demand.

V. CONCLUSIONS

A hydrogen network including converters (electrolyzer and fuel cell), storage, and demand (car refuelling) was proposed and studied in detail here as part of an integrated energy system with electricity, gas and heat production and demand. The analyses show that due to storage capability of this energy carrier, even more flexibility on energy conversion inside the hubs is provided, which brings about more freedom in system planning and operation. The performed studies prove that the inclusion of electrolyzers along with hydrogen storage devices in the hubs is beneficial, as there is a possibility of hydrogen production and storage through a high efficiency energy pathway, during the time intervals in which low price electricity is available. However, electricity production by fuel cells as part of energy hubs (not in cars), is not desirable because of its relatively lower efficiency; from the presented studies, one can conclude that higher efficiencies of these particular converters, or lower hydrogen prices, would be required to make them more feasible for realistic inclusion in integrated energy systems.

APPENDIX

This appendix provides the data of the integrated energy system and hubs depicted in Fig. 2. Tables I to III show the data for individual energy networks [7], while tables IV and V show the data for all the converter and storage devices inside the hubs.

TABLE I
DATA OF ELECTRICITY NETWORK

G_1	Slack, $a^t_{G_1} = 0\left[\text{mu}\right], c^t_{G_1} = (10^{-4}).b^t_{G_1}\left[\text{mu.pu}^{-2}\right]$
G_2	PQ, $a^t_{G_2} = 0\left[\text{mu}\right], c^t_{G_2} = (10^{-4}).b^t_{G_2}\left[\text{mu.pu}^{-2}\right]$ $0 \le P^t_{G_2} \le 4, 0 \le Q^t_{G_2} \le 4, 0 \le S^t_{G_2} \le 5$ all in [pu]
load	as in Fig. 4
bus voltage	$0.9 \le \left\|V^t_m\right\| \le 1.1\left[\text{pu}\right]$
line 1-2	$\overline{Z}_{12} = .3 + j.9\left[\text{pu}\right], \overline{Y}_{12} = j1.5(10^{-6})\left[\text{pu}\right]$
line 1-3	$\overline{Z}_{13} = .2 + j.6\left[\text{pu}\right], \overline{Y}_{13} = j2.5(10^{-6})\left[\text{pu}\right]$
line 2-3	$\overline{Z}_{23} = .1 + j.4\left[\text{pu}\right], \overline{Y}_{23} = j3.5(10^{-6})\left[\text{pu}\right]$

TABLE II
DATA OF NATURAL GAS NETWORK

N	known-pressure, $a^t_N = 0\left[\text{mu}\right], b^t_N = 5\left[\text{mu.pu}^{-1}\right], c^t_N = 0\left[\text{mu.pu}^{-2}\right]$
load	as in Fig. 4
nodal pressure	$0.8 \le \pi^t_m \le 1.2\left[\text{pu}\right]$
pipe 1-2	$GHV.k_{12} = 4.5$
pipe 1-3	$GHV.k_{13} = 3.0$
pipe 2-3	$GHV.k_{23} = 2.0$
C_{12}, C_{13}	$GHV.k_{C_{12}} = GHV.k_{C_{13}} = 0.5\left[\text{pu}^{-1}\right]$ $1.2 \le \pi^t_m / \pi^t_k \le 1.8$

TABLE III
DATA OF HEAT & HYDROGEN NETWORKS

H_2	locally available with: $0 \le P^t_H \le 3\left[\text{pu}\right]$
h	locally available with: $0 \le P^t_h \le 3\left[\text{pu}\right]$

TABLE IV
DATA OF CONVERTER DEVICES

Converter device	Maximum output power [pu]	Efficiencies [%]
Rectifier & Electrolyzer	0.5	elec/H2: 85, thermal: 15
Fuel cell & Inverter	0.5	H2/elec: 55, thermal: 45
Heat exchangers	-	thermal: 90
Transformer	1.5	elec: 98
Gas turbine	1	elec: 35, thermal: 45
Furnace	1.5	thermal: 75
Compressor	0.5	elec/air: 80, thermal: 20

TABLE V
DATA OF GAS, HEAT, AND HYDROGEN STORAGE DEVICES

Min/max exchange power [pu]	-0.5/0.5
Min/max stored energy [pu]	0.1/0.5
Standby losses [pu]	0.05
Charging efficiency [%]	95
Discharging efficiency [%]	95

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