Optimal Power Dispatch of Energy Networks including External Power Exchanges

A.J. del Real, M.D. Galus, C. Bordons and G. Andersson

Abstract— **This paper presents a revision of a general framework which allows a standard modeling and optimization of arbitrary complex energy networks including multiple interconnected energy carriers, the so–called *energy hubs*, which are defined as interfaces among energy producers, consumers and the transportation infrastructure. In particular, the main contribution of this work arises from the explicit introduction in the modeling framework of external power exchanges from other surrounding networks and *network peripheral hubs*. Also, the impact of hydrogen storage in a network including electricity, natural gas and wind is studied by means of the proposed general network formulation, showing its high flexibility in terms of modeling detail and accuracy.**

I. INTRODUCTION

The energy infrastructures of today are about to undergo a profound change: fossil fuel prices are raising every year while energy demand increases in every country. Also, the aim to reduce greenhouse gas emissions is moving its attention to more environmentally–friendly and sustainable renewable energy sources. At the same time, developed countries have restructured monopolistic energy frameworks in order to liberalize markets, which has provided access for new participants.

As a result, energy generation is becoming more decentralized, with an increasing number of small distributed renewable energy resources [1]. By the way, one of the main problems associated with renewable energy systems is the reliability and quality of the power supply. As a matter of fact, since the renewable source is intermittent, unpredictable fluctuations may appear in the output [2]. Also, electrical generation from renewable sources in not subject to demand, which creates imbalance in the system. One way to overcome this problem is by including intermediate storage [3]. Among the most promising storage technologies are those based on hydrogen, which is expected to be used for very different applications, such as automotive [4], [5] and stationary power generation [6] applications, as they constitute some interesting advantages in terms of cost, autonomy, power range and environmental effects [7].

Due to the great complexity of such energy systems including intermediate storage and multiple, decentralized and intermittent generators, new approaches have to be done in order to study these new systems. Therefore the development of an integrated modeling and analysis framework for multi–carrier energy systems represents an essential need for future research.

Traditionally, energy networks have been considered employing only one form of energy, i.e, electricity [8] or natural gas [9]. More recent works combined modeling and analysis of energy systems including multiple energy carriers [10], [11] and system interactions and the integrated planning of natural gas, electricity, and other networks [12], [13]. Moving to a more general approach, [14] and other related papers by the same authors such as [15], [16], [17], [18] proposed a modeling framework which enables integration of an arbitrary number of energy carriers as well as chemical reactants and products, introducing the *energy hub* concept, defined as a general interface among energy producers, consumers and the transportation infrastructure. Such general formulation allows high flexibility in terms of modeling detail and accuracy, while any technology for transmission, conversion, and storage of energy can be considered. Moreover, the energy hub concept has also been recently adapted in other research fields proving its flexibility, i.e., modeling of PHEV (Plug–in Hybrid Electric Vehicles) [19]

This work is a revision of the appointed general formulation for networks composed by multiple interconnected hubs, but now explicitly introducing network power exchanges with other surrounding networks and also via *peripheral hubs*, a new concept introduced herein. This consideration allows hubs to be treated also as network power injectors taking advance of a renewable energy source. Once the network model is obtained, an optimal operating policy (the so-called *Optimal power dispatch* of energy networks) based on prior knowledge of estimated conditions (such as energy demands or wind speed predictions) while minimizing an objective function can be addressed, which are useful as a basis of comparison for the evaluation of real–time control strategies quality [15].

This way, the mathematical framework of the modeling and optimization problem is presented in the following section, also remarking the main contributions of this work. Section III propose a possible application of the concepts revised herein to a network including electricity, natural gas, wind power generation and hydrogen storage. Section IV discusses the simulation results obtained, showing the impact of hydrogen storage in the studied network. Lastly section V is dedicated to the concluding remarks.

II. MATHEMATICAL FORMULATION

As appointed in section I, there are a number of approaches to formulate multiple carrier systems, such as

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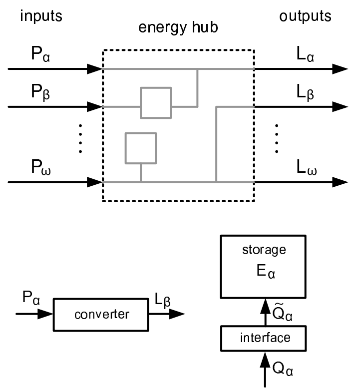

Fig. 1. Energy hub diagram and basic elements

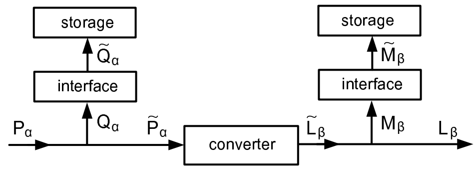

Fig. 2. Converter with storage at input and output sides

"energy–services supply systems" [10], "basic units" [11], "microgrids" [20] and the so–called "hybrid energy hubs" [21]. This section is dedicated to the latter formulation.

A. Energy Hub Modeling

Energy hubs contain three basic elements: direct connections, converters and storage (see fig. 1). With respect to converters, they link inputs $\mathbf{P}$ and outputs $\mathbf{L}$ through the *converter coupling matrix* $\mathbf{C}$:

$$\underbrace{\begin{bmatrix} L_\alpha \\ \vdots \\ L_\omega \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} c_{\alpha,\alpha} & \dots & c_{\omega,\alpha} \\ \vdots & \ddots & \vdots \\ c_{\alpha,\omega} & \dots & c_{\omega,\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha \\ \vdots \\ P_\omega \end{bmatrix}}_{\mathbf{P}} \tag{1}$$

the set of energy carriers being denoted by $\mathcal{E}$ and its members specified by small Greek letters:

$$\alpha, \beta, \dots, \omega \in \mathcal{E} = \{\text{electricity}, \text{hydrogen}, \dots\}$$

Furthermore, each hub i contains a set of converters $\mathcal{C}_i$. The subset $\mathcal{C}_{i\alpha} \subseteq \mathcal{C}_i$ contains all elements of hub i which convert α into another carrier:

$$k \in \mathcal{C}_{i\alpha} = \{1, 2, \dots, N_{\mathcal{C}_{i\alpha}}\}$$

As the input flow P_α can be distributed among various converter devices, *dispatch factors* $\nu_{\alpha k}$ specify how much of the input power P_α flows into the converter k:

$$P_{\alpha k} = \nu_{\alpha k} \, P_\alpha \tag{2}$$

With respect to storage, the storage interface can be modeled similar to a converter device, with steady-state input and output power values Q and $\tilde{Q}$ related to each other as:

$$\tilde{Q}_\alpha = e_\alpha Q_\alpha \tag{3}$$

where e_α the efficiency of the charge/discharge storage interfaces, expressed as:

$$e_\alpha = \begin{cases} e_\alpha^+ & \text{if } Q_\alpha \geq 0 \quad \text{(charging/standby)} \\ 1/e_\alpha^- & \text{else} \quad \text{(discharging)} \end{cases} \tag{4}$$

The stored energy after a certain operating period T equals the initial storage content plus the time integral of the power. For steady-state considerations, power can be approximated by the change in energy ΔE during a time period Δt, assuming a constant slope $\dot{E}_\alpha = dE_\alpha/dt$, resulting:

$$E_\alpha(T) = E_\alpha(0) + \int_0^T \tilde{Q}_\alpha(t) \, \mathrm{d}t \simeq E_\alpha(0) + \Delta E_\alpha \tag{5}$$

Adding the storage to the hub equation (1) and taking into account which side of the converter the storage is located lead to (see fig. 2):

$$\left[\ \mathbf{L} + \mathbf{M} \ \right] = \mathbf{C} \left[\ \mathbf{P} - \mathbf{Q} \ \right] \tag{6}$$

Rewriting (6) in a more condensed form and defining $\mathbf{M^{eq}}$ as shown, the following equation results:

$$\mathbf{L} = \mathbf{C} \left[\ \mathbf{P} - \mathbf{Q} \ \right] - \mathbf{M} = \mathbf{C}\,\mathbf{P} - \mathbf{M^{eq}} \tag{7}$$

Also, defining the *storage coupling matrix* $\mathbf{S}$ to describe how changes of the storage energy derivatives affect the hub output flows, the equivalent storage power flows $\mathbf{M^{eq}}$ can be stated as:

$$\underbrace{\begin{bmatrix} M_\alpha^{eq} \\ \vdots \\ M_\omega^{eq} \end{bmatrix}}_{\mathbf{M^{eq}}} = \underbrace{\begin{bmatrix} s_{\alpha\alpha} & \dots & s_{\omega\alpha} \\ \vdots & \ddots & \vdots \\ s_{\alpha\omega} & \dots & s_{\omega\omega} \end{bmatrix}}_{\mathbf{S}} \underbrace{\begin{bmatrix} \dot{E}_\alpha \\ \vdots \\ \dot{E}_\omega \end{bmatrix}}_{\dot{\mathbf{E}}} \tag{8}$$

Summarizing all the previous equations, the complete hub energy model would be:

$$\mathbf{L} = \mathbf{C}\,\mathbf{P} - \mathbf{S}\,\dot{\mathbf{E}} \tag{9}$$

B. Interconnection of Energy Hubs

An energy network can be modeled as the interconnection of energy hubs (see fig. 3). Like this, a set of energy hubs $\mathcal{H}$ is considered, whose members are denoted by small Roman letters, $N_\mathcal{H}$ being the total number of energy hubs:

$$i, j \in \mathcal{H} = \{1, 2, \dots, N_\mathcal{H}\}$$

Also, network nodes are denoted as the set $\mathcal{N}$, considering $N_\mathcal{N}$ as the total number of nodes in the system:

$$m, n \in \mathcal{N} = \{1, 2, \dots, N_\mathcal{N}\}$$

In a network formulation, energy conversion and storage are defined by the converter and storage coupling matrices $\mathbf{C}_i$ and $\mathbf{S}_i$ of all hubs $i \in \mathcal{H}$, respectively:

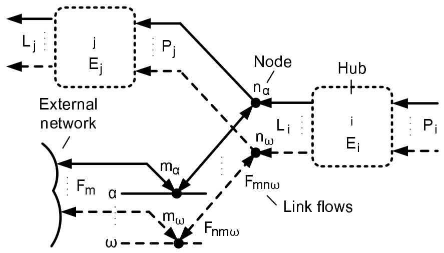

Fig. 3. Network concept depicting external power exchanges and peripheral hubs

$$\mathbf{L}_i = \left[\begin{array}{cc} \mathbf{C}_i & -\mathbf{S}_i \end{array}\right] \left[\begin{array}{c} \mathbf{P}_i \\ \dot{\mathbf{E}}_i \end{array}\right] \quad \forall\, i \in \mathcal{H} \tag{10}$$

Network power exchanges are defined by: (a) external power exchanges from other surrounding networks (F_m would be the exchanged power in node m) and (b) peripheral hubs' power inputs and outputs (which would be P_i and L_j in the network shown in fig. 3), defining a subset $\mathcal{H}_p \in \mathcal{H}$ where some of its members' inputs or outputs are not connected to a node:

$$k, l \in \mathcal{H}_p = \{1, 2, \ldots, N_{\mathcal{H}_p}\} \tag{11}$$

where $N_{\mathcal{H}_p}$ is the total number of peripheral hubs in the network. Also, link flows of the energy carrier α between hubs m, n are denoted with $F_{mn\alpha}$.

Finally, the information how energy hubs are connected in the network can be summarized as:

$$\mathbf{G}_\alpha\left(\mathbf{F}_\alpha, \mathbf{P}_i, \mathbf{L}_i\right) = 0 \quad \forall\, \alpha \in \mathcal{E} \tag{12}$$

C. Optimal Power Dispatch Formulation

The aim of the *Optimal Power Dispatch* optimization carried out herein is the determination of an optimal operating policy of a network of interconnected energy hubs.

Mathematically, the problem can be stated as a multi-period (MP) non-linear constrained optimization problem, as the inclusion of storage requires to consider multiple time periods due to the fact that the storage state at a certain period depends on the preceding periods.

This way, for specified hub power demands and available power supplies, the optimal hubs' in- and outputs, dispatch factors, equivalent storage power flows, network power flows and external power injections are calculated in order to minimize a certain objective function subject to hubs and network parameters, limitations and topologies.

In particular, the objective function (13a) may depend on the consumption of energy hubs, stored energies, dispatch factors, network flows and external power injections. Equality constraints (13b,13c) are given by the power flow equations of the hubs and the network. Inequality constraints arise from limitations of hub inputs (13d), stored energies (13e,13f) (the latter equation introduced to force sustainable storage utilization), equivalent storage power flows (13g,13h), network internal flows (13i), individual converters (13j,13k) and external power exchanges (13l,13m).

TABLE I

ENERGY HUB LOADS

Hub loads	Value (pu)
Hub #1 electricity	0.75
Hub #1 heat	0.5
Hub #2 electricity	1
Hub #2 heat	0.5
Hub #4 electricity	1.25
Hub #4 heat	1

The corresponding lower and upper bounds are defined in vectors $\underline{\mathbf{P}}_i, \overline{\mathbf{P}}_i, \underline{\mathbf{E}}_i, \overline{\mathbf{E}}_i$, storage energy ramping limits $\underline{Q}_{i\rho}, \underline{M}_{i\rho}, \overline{Q}_{i\rho}, \overline{M}_{i\rho}$ (depending on which side of the converter the storage is placed), link flow limits $\underline{F}_{mn\alpha}, \overline{F}_{mn\alpha}$, individual converter limits $\underline{P}_{i\alpha k}, \overline{P}_{i\alpha k}$, peripheral hubs' output power demand and input power availability $\underline{\mathbf{P}}_j, \overline{\mathbf{P}}_j$ and external power exchanges from other networks demands and availability $\underline{F}_{n\alpha}, \overline{F}_{n\alpha}$.

$$\begin{array}{llll}
\text{Minimize} & \displaystyle\sum_{t=1}^{N_t} \mathcal{F}^t\left(\mathbf{P}_i^t, \nu_{i\alpha k}^t, \mathbf{E}_i^t, \mathbf{F}_\alpha^t\right) & & \text{(13a)} \\
\text{subject to} & \mathbf{L}_i^t - \mathbf{C}_i^t\, \mathbf{P}_i^t + \mathbf{M}_i^{\text{eq}\,t} = \mathbf{0} & \forall t, \forall i & \text{(13b)} \\
& \mathbf{G}_\alpha^t = \mathbf{0} & \forall t, \forall \alpha & \text{(13c)} \\
& \underline{\mathbf{P}}_i \le \mathbf{P}_i^t \le \overline{\mathbf{P}}_i & \forall t, \forall i & \text{(13d)} \\
& \underline{\mathbf{E}}_i \le \mathbf{E}_i^t \le \overline{\mathbf{E}}_i & \forall t, \forall i & \text{(13e)} \\
& \mathbf{E}_i^0 \le \mathbf{E}_i^{N_t} & \forall i & \text{(13f)} \\
& \underline{Q}_{i\rho} \le Q_{i\rho}^t \le \overline{Q}_{i\rho} & \forall t, \forall i, \forall \rho & \text{(13g)} \\
& \underline{M}_{i\sigma} \le M_{i\sigma}^t \le \overline{M}_{i\sigma} & \forall t, \forall i, \forall \sigma & \text{(13h)} \\
& \underline{\mathrm{F}}_{mn\alpha} \le \mathrm{F}_{mn\alpha}^t \le \overline{\mathrm{F}}_{mn\alpha} & \forall t \forall m, n \forall \alpha & \text{(13i)} \\
& \underline{P}_{i\alpha k} \le \nu_{i\alpha k}^t P_{i\alpha}^t \le \overline{P}_{i\alpha k} & \forall t, \forall i, \forall \alpha, \forall k & \text{(13j)} \\
& 0 \le \nu_{i\alpha k}^t \le 1 & \forall t, \forall i, \forall \alpha, \forall k & \text{(13k)} \\
& \underline{\mathbf{P}}_j \le \mathbf{P}_j^t \le \overline{\mathbf{P}}_j & \forall t, \forall j & \text{(13l)} \\
& \underline{F}_{n\alpha} \le F_{n\alpha}^t \le \overline{F}_{n\alpha} & \forall t, \forall n, \forall \alpha & \text{(13m)}
\end{array}$$

where $t \in \{1, 2, \ldots, N_t\}$; $i \in \mathcal{H}$; $j \in \mathcal{H}_p$; $\alpha, \beta \in \mathcal{E}$; $k \in \mathcal{C}_{i\alpha}$; $m, n \in \mathcal{N}$. Energy carriers $\rho \in \mathcal{E}$ are stored at the input side of the hub, the carriers $\sigma \in \mathcal{E}, \sigma \neq \rho$ are stored at the output side.

III. APPLICATION

The optimal power dispatch formulation according to the general energy hub model is adopted herein for the four hub network depicted in figure 4. The network consists of four hubs which represent different areas with electric and heat loads, respectively. For simplicity, hub loads are assumed constant (see table I, where the values are given in power units, pu).

Hubs 1, 2 and 4 are interconnected by electricity lines and gas pipelines. Each of those hubs includes a transformer, a microCHP (Combined Heat and Power) and a furnace supplying the individual loads. They can be modeled through the following energy hub equation, directly derived from (1).

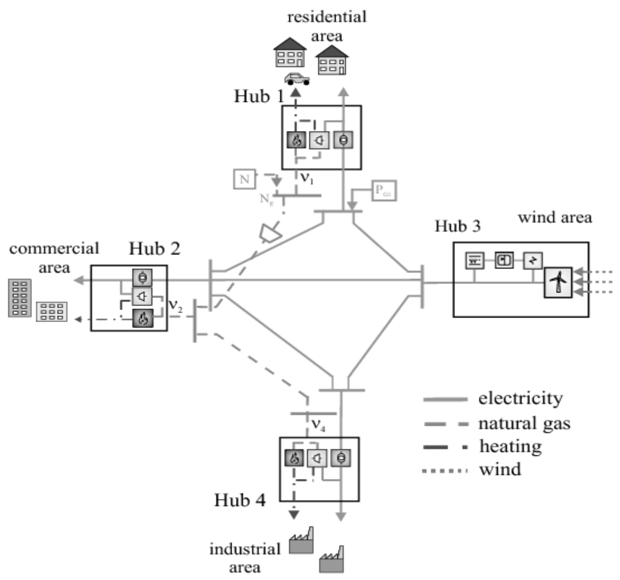

Fig. 4. Network for case study

$$\underbrace{\begin{bmatrix} L_{i\,e}^t \\ L_{i\,h}^t \end{bmatrix}}_{\mathbf{L}} = \underbrace{\begin{bmatrix} \eta_{ee}^{TR} & \nu_{i\,g}^t \eta_{ge}^{CHP} \\ 0 & \nu_{i\,g}^t \eta_{gh}^{CHP} + (1-\nu_{i\,g}^t)\eta_{gh}^F \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_{i\,e}^t \\ P_{i\,g}^t \end{bmatrix}}_{\mathbf{P}} \tag{14}$$

In (14), $L_{i\,e}^t$ and $L_{i\,g}^t$ are the electric and heat loads in each time step for hubs $i = 1, 2, 4$, η_{ee}^{TR} is the transformer efficiency chosen to be 0.8, $\nu_{i\,g}^t$ is the dispatch factor at hub i in t and $\eta_{ge}^{CHP}\eta_{gh}^{CHP}$ are the efficiency of the CHP for electricity and heat production, chosen to be 0.35 and 0.45, respectively. The efficiency of the furnace (F) is assumed to be 0.9. Electric power and natural gas are injected at hub one. The wind in-feed and conversion occurs at hub 3. It consists of a wind generator, an electrolyzer, a hydrogen storage and a fuel cell and is interconnected with all other hubs via electricity lines. The wind is indicated via the grey arrows. The hub equation is different than the others and is formulated according to (3)-(9) by

$$L_{3\,e}^t = P_w^t - \frac{1}{e_{h_2}} \dot{E}_{h_2}^t \tag{15}$$

with $\dot{E}_{h_2}^t = E_{h_2}^t - E_{h_2}^{t-1}$

$$e_{h_2} = \begin{cases} \eta_{elec} & \text{if } \dot{E}_{h_2}^t \geq 0 \quad \text{(charging/standby)} \\ -\frac{1}{\eta_{FC}} & \text{else} \quad \text{(discharging)} \end{cases}$$

where $\eta_{elec} = 0.8$ and $\eta_{FC} = 0.65$ are the efficiencies of electrolyzer and fuel cell, respectively. Wind generators are built only for an interval of wind speeds. If the wind becomes too strong the wind generator needs to be switched off and no wind in-feed is apparent to be injected into the network. Therefore the constraint vector stated in (13l) incorporates the wind generator model, considering a 20 pu maximum power generator, introducing the function c_w and where W_s^t is the actual wind speed and P_w^t is the power generated by the wind generator:

$$0 \leq P_w^t \leq c_w W_s^t \tag{16}$$

with

$$c_w = \begin{cases} 0 & \text{if } W_s^t < 5 \\ 2 - 10/W_s & \text{if } 5 \leq W_s^t < 15 \\ 20/W_s & \text{if } 15 \leq W_s^t < 25 \\ 0 & \text{if } W_s^t \geq 25 \end{cases}$$

The electric lines were modeled through an AC power flow formulation [22]. For each node or hub a nodal power balance according to (17) can be stated, where $\mathcal{N}_m \subseteq \mathcal{N} \setminus m$ is the set of nodes connected to m and F_{me} denotes the injected electric power at node m. The electric power F_{mne} flowing from node m to node n is calculated using (18). Here, θ_m is the angle of the power phasor at node m and Z_{mn} is the series admittance between nodes m and n determined by the frequency ω, the line inductance $L^{'}$ and the length of the line l_{mn}. For simplicity, $Z_{mn} = 20$ for every electric line.

$$F_{me} - \sum_{n \in \mathcal{N}_m} F_{mne} = 0 \tag{17}$$

where

$$F_{mne} = \frac{\theta_m - \theta_n}{Z_{mn}}, \; Z_{mn} = \omega L^{'} l_{mn} \tag{18}$$

Gas networks can basically be modelled in the same way as power networks using gas nodal balance and line equations, respectively. Similarly to (17), the flow balance for an arbitrary node m can be stated as

$$F_{mg} - \sum_{n \in \mathcal{N}_m} F_{mng} = 0 \tag{19}$$

where F_{mg} is the volume flow injected at node m. Flows between nodes can be expressed as functions of the upstream and downstream pressures p_m and p_n, respectively, and properties of the pipeline and the fluid are represented by the constants k_{mn} [17], chosen here to have a constant value of 10.

$$F_{mng} = k_{mn} s_{mn} \sqrt{s_{mn} \left(p_m^2 - p_n^2\right)} \tag{20}$$

where

$$s_{mn} = \begin{cases} +1 & \text{if } p_m \geq p_n \\ -1 & \text{else} \end{cases} \tag{21}$$

In contrast to electricity lines where theoretically no active power is necessary to maintain a certain voltage, generation of pressure through compressors needs power. If the compressor is driven by a gas turbine, the corresponding power consumption can be considered as additional power flowing into the pipeline section as shown in figure 5. The amount of power consumed by the compressor depends on the pressure added to the fluid and the volume flow rate through it. Using the notation of figure 5 the compressor demand can be approximated with

$$F_{com} = k_{com} F_{mng} \left(p_m - p_k\right) \tag{22}$$

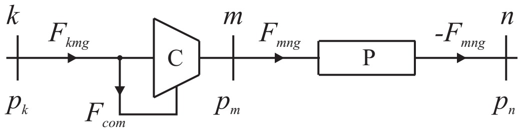

Fig. 5. Model of transmission link with compressor (C) and pipeline (P).

TABLE II
EXTERNAL POWER INJECTION PRICES

External power injection	Price (mu)
Π_{e1}	9
Π_{e2}	0.09
Π_{g1}	8
Π_{g2}	0.08

where k_{com} is a constant characterizing the compressor unit; p_k and p_m are the suction and discharge pressures, respectively [17].

The volume flow rate F_{mng} corresponds to power flow P_{mng}; the relation between volume and power flow is given by

$$P_{mng} = GHV \cdot F_{mng} \qquad (23)$$

where GHV is the gross heating value of the fluid.

Lastly, cost function (13a) to be minimized would here depend on electricity and natural gas prices, taking into account that wind price is set to 0. Prices, given in monetary units (mu), are shown in table II, the cost function being

$$\Pi_{e1}F_e + \Pi_{e2}F_e^2 + \Pi_{g1}F_g + \Pi_{g2}F_g^2 \qquad (24)$$

where F_e and F_g are the total electric and natural gas power injected in the network, respectively.

IV. SIMULATION RESULTS

The system introduced in the last two sections is simulated according to the optimization routine denoted in (13a)-(13m), using MATLAB and the commercial solver CPLEX. As the solver can only handle linear systems, the network equations had to be firstly linearized. The interval for the subsequent time steps was chosen to be 1h. Blatantly, the wind intermittency is very high and the intensity of the wind can vary within an hour vigorously. However, in order to show the feasibility of the concept while saving computational power only 24 intervals were simulated. Note that the scheme is easily extendable.

Figure 6(a) shows the wind power in-feed after normalization for the hub network in pu (per unit). In this example (based on real wind speed data), the most power in-feed from wind occurs during the night and early morning hours. During the day no wind is apparent. Figure 6(b) depicts the direct wind power injection into the hub network and the energy in eu (energy per unit) which is stored in the hydrogen tank. In figure 6(c) the utilization of energy sources for the network other than wind power is visualized.

As very high wind power is apparent during the night, the optimization routine finds a high injection of electric

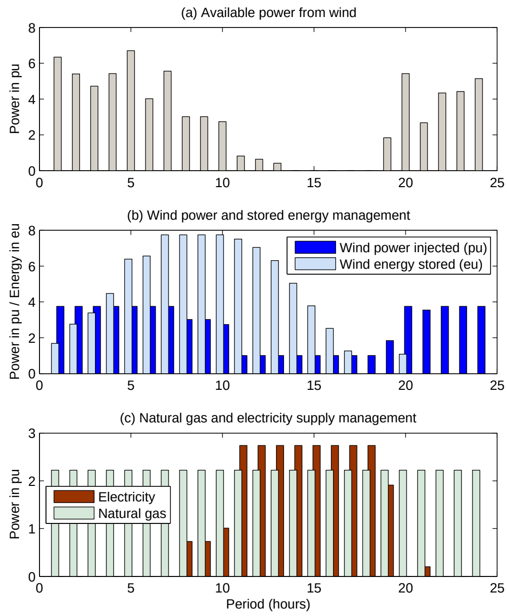

Fig. 6. Optimization results
(a) Available wind power
(b) Injected and stored wind power
(c) Electricity and natural gas deployment

power from wind into the network supplying the complete load. Furthermore, enough wind is available to charge the hydrogen storage at the highest rate. In the morning the wind power is decreasing which leads to a constant state of charge of the hydrogen tank because the electricity generated from wind is supplying the system load. At 8 a.m. pricy electricity injections at hub 1 are apparent although wind power is still available and the hydrogen tank is containing enough energy to be utilized for the network. Clearly, the hydrogen stored in energy is saved for later phases in the day when no wind is apparent at all. While the day is proceeding, the wind power decreases. This results in an increased utilization of the storage with the fuel cell replacing parts of the electricity that would need to be injected to supply the total system load. In the late afternoon the storage is fully depleted resulting in a high injection of electricity for which the market price needs to be paid. As the wind power increases in the evening hours the system load can be fully supplied by the wind power, again. However, the wind is not strong enough to recharge the hydrogen storage.

Summarizing the scheme, the optimization routine chooses to replace the energy needed in the system through wind power as it is freely available. The storage is recharged during high wind power intervals and depleted while the load is high and the wind is not apparent. The utilization of natural gas is used at a constant level, as heating loads were supposed herein to be constant.

For analyzing the total system costs, figure 7 plots the savings introduced to the system when utilizing a hydrogen

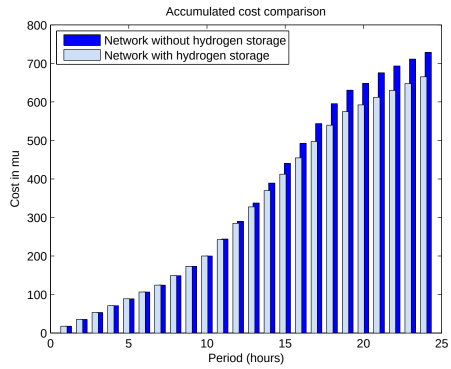

Fig. 7. Accumulated cost comparison for network with/without hydrogen storage

storage on an 24h basis. The costs for the systems with and without hydrogen storage are equal in the early day hours as the wind power supplies the electric load completely and the heat load cannot be supplied in another way than by utilizing natural gas. The difference that the excrescent power from the wind would be lost is not yet taken into account as the storage is not yet of importance. However, later during the day, more power would be needed from the slack node because the wind stops but the loads still have to be supplied. This amount of electricity is actually expensive and introduces additional costs in case of a missing storage. When utilizing the hydrogen storage some of the electricity that would need to be bought from the market is replaced by the renewable energy stored at a high efficiency in the hydrogen tank. In fact, the constant utilization of renewables throughout the day results in a significant cost decrease for the complete system. After 24h the costs are lowered to a total of 665 mu (monetary units) for the hydrogen storage case. The maximal cost of the system (without any storage) is 728 mu, therefore the savings are found to be around 9% within 24h. Considering that lots of the system costs are rooting from the utilization of natural gas, substantial savings can be implemented utilizing an hydrogen storage.

V. CONCLUDING REMARKS

This paper introduces an energy hub model for a multi energy carrier network. It integrates an intermittent power source chosen to be wind and utilizes an electrolyzer, a hydrogen tank and a fuel cell as a flattening storage system. The optimization proves that the hydrogen storage is capable to mitigate or even completely avoid power consumption from non-renewable sources when utilized with a renewable and highly intermittent source like wind. Furthermore, considering the economic side of hydrogen power utilization, the paper finds substantial savings for the system when utilizing the storage system.

Further investigations will focus on specific network constraints, costs changing along the optimization period, utilization of a more exact wind power signal and more economic considerations for hydrogen integration, referring to a possible future "hydrogen economy".

VI. ACKNOWLEDGEMENTS

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