Abstract—The network model bases upon the energy hub concept, which was developed by the Vision of Future Energy Networks” (VoFEN) research group at ETH Zurich in the last years. Keynote of the concept is a combined optimization of different energy carrier. Synergetic effects are expected to give unusual optimization results, when allowing any possible energy conversion inside a specific area that constitute the hub. Costs for the energy consumption or production are generally used as the optimization criteria. Any technologies for conversion and storage are integrated in a coupling matrix, which links input and output. This paper deals with an extension to the optimization part by merging the network flows with the pricing of grid costs. The impact of network flow pricing is at first derived from theory, then translated into the energy hub concept and finally illustrated in an example.

I. INTRODUCTION

Any holistic strategy for energy infrastructure planning should regard all energy carriers – not only electricity. Pursuant to the World Energy Outlook 2008 [1] the share of electricity in the total final consumption in 2030 rises from 17% to 21% global, from 19% to 22% in the European Union and from 24% to 30% in Japan. The share of fossils in the electricity generation remains at a high level, 66% in 2030 global. So why focus on energy grids for each carrier separately, when looking for the optimal coupling? Continuing the work of [2], where a detailed network description and modeling for multi-energy systems was presented, this paper merges the network theory with the possibilities of electricity markets. The focus is put on the network, which is corresponding to the transmission level in electricity grids. An earlier work [3] already discussed the modeling of renewable energy feed-in at the distribution level. Following the EU directives from 1996 for the electricity and 1998 for the gas market, the rules caused liberation to a greater extend. The unbundling of energy generation, power transmission and distribution yields to a more transparent situation for the consumer. Even more, the tax authorities can now collect money from the TSOs, because the income of the generation cannot be balanced with the costs for the grid infrastructure and support any longer. For any modeling and optimization of energy this trend should be taken into account. But how does the suggested concept differ from assimilable models and theories?

II. BACKGROUND

To better understand the scope of the VoFEN project and what it focuses on, one needs to keep in mind that it is built on a Greenfield approach and therefore does not go deep into the actual implementation. However, some benchmarks and guidelines need to be established, and in that view, the comparison will be made with regards to smart or intelligent grids, what level of abstraction in the physical layer of the grid is used, and a brief overview to similar projects already implemented. The latter will include the differences in terms of goals envisioned. For smart grids, the comparison will focus on elements given by [4] in the article, as quoted in Fig. 1.

![Fig. 1: Smart grid layers](image-url)

First layer falls into the category of today’s infrastructure with all the classical active and passive elements such as cables, transformers, switches, breakers, shunts, etc. All conversion based of the above can be mathematically represented in the hub concept with the appropriate element in the matrix of a specific hub. The added capability of additional plug-and-model carriers of energy (natural gas, district heating) and future carriers such as hydrogen are not yet part of the smart grid. Some of these needs, like transportation and storage, are already envisioned via the interconnector part of the hub concept in [5] or under development, which enables seamless transforming between different energy carriers in the grid. Since the energy hub concept is more of a theoretical framework, many elements (breakers, shunts, etc.) are not implied, which has to be stated as well for the next layer.

Layer two would form the basis of the future smart or intelligent grid, however since this concept is also in the making...
there isn’t much that can be discussed for the moment in terms of real technology and the hub concept at hand. The foundations, on the other hand, are specified, and in words of European Commission a smart grid should: fulfill customers’ needs, be accessible (particularly to renewable sources and distributed generation), reliable, economical with level playing field.

Communication layer three is envisioned as a means of delivering the data gathered by sensors back to those who need it. As such, the concept parts way with the dumb components of the grid, employing sensors to enable every part of the grid to become self-aware and do its part in keeping the system responsive and reliable. These instruments can range from simple power meters with real-time monitoring (which is the current extent of implementations of smart grids) to state-of-the-art ZigBee wireless mesh networks. Some of the planned implementations do face a security issue [7] regarding client privacy and system intrusions that can disrupt the integrity of the supply grid. Also envisioned is a two-way communication with adequate broadband bandwidth implemented from the beginning to cut down on retrofit costs, supporting all the foreseeable needs, hopefully in a standardized manner, such as the one currently in making (e.g. IEEE 802.15.4). Inside the VoFEN project communication between hubs is an ongoing work package.

Finally, decision intelligence is the pinnacle of the proposed system where all the changes and improvements implemented in the infrastructure should deliver on the promise of cheaper, more reliable and efficient service. The proposed tools would certainly involve SCADA-like type of software, with business intelligence tools in planning and decision support steps for such a grid. Due to the high level of automation, there would need to be several conceptually different analytical models, and only if a majority of the models agree on an action, to automatically execute it. In other cases, a human presence would still be required to resolve conflicts. One major advantage for the energy hub concept is logical separation of actual ownership of the infrastructure and addition of an abstract layer for the management of the grid in a way that best suits the needs and circumstances. Therefore, an operator for a specific area can choose whether it will manage and be responsible for the grid on its own, or have it outsourced to the top-level authority and pay a fee for the service.

Moving on to similar concepts, one particularly stands out as a successful example of simulating and optimizing multi-carrier energy flows [8]. However, there are significant differences between the two. Emphasis is heavily given towards hydropower, due to the circumstances in Scandinavia. Also, all of the proposed models work with what is essentially as-is state of the grid and do not have a goal of changing the approach. Final outcome of the analysis is to produce a more capable system dealing with specific local conditions, integrating two energy carriers for the time being and dealing with energy market along the way.

This concept is similar in terms of that it is as well done in MATLAB, with programming techniques that are in the core identical to the ones used in the hub concept. Planning timeline fits as well within the 50-year prediction horizon. However, hub concept has a few distinctive advantages compared to the Scandinavian grid. Time resolution on the acquired data is several orders of magnitude larger in the observed case compared to Scandinavia. Generally, the observed data is measured at an interval of 15 minutes. Scandinavian case gives as a reference of anything between four measurements per week and a yearly average, which is insufficient for any kind of real-time monitoring. The number of nodes and geographical area regarded for the simulation is the most emphasized contrast between the two cases. As one takes an entire region with 125+ nodes, other focuses on a small area with only eleven nodes in the most advanced case study. Considerable advantage to such low-level approach is superior modeling of the nodes, more in line with a microgrid approach, giving lower margins of error as a final result.

Ultimately, the goal of such a model is to provide the basic framework for a host of new technologies that are on the horizon. Some of those are smart grid features that by some quotes could end up controlling almost 30% of the total power consumption [10], or smart power meters that can detect and report consumption in real time, thus making time-based energy pricing a reality and enabling better usage of existing power generation facilities. The enabling part of the big picture will be the mathematical modeling and long term data acquisition done on the Baden showcase that will be described in the next chapter.

Fig. 2: Network example with three nodes and three hubs

III. NETWORK DESCRIPTION

Despite the risk to repeat at this point, following the basics of the multi-energy network idea are explained. At the beginning of this paper the hub was introduced as a conglomerate of energy production, consumption, conversion and storage inside certain range. The area of the GIS-layer in Fig. 2 can be split up into three hubs $\Omega_i$, which are drawn in the hub-layer. This choice is appropriate when looking at physical separations in the area, like streets or forests, and if the hubs furthermore represent a unique behavior. Hub 2 might be office buildings, whereas hubs 1 and 3 are dwellings, of which one is using natural gas and the other fuel oil
for heating purpose. Details about the hubs are not of special interest in this paper, since they are mentioned in [2], [3] and on the project’s homepage [9]. The equation describing the hub is written in (1) and shown in Fig. 3. The layer superior to the hubs is the node-layer and contains the nodes $\mathcal{N}_i$, which are the connection between hubs and to the external grid $\mathcal{E}$.

$$
(L_i + T_i + M_i) = C_i \cdot (P_i + R_i - Q_i)
$$

A universal connection between two hubs $i$ and $j$ is drawn in Fig. 4. The transition from hub-layer to node-layer is represented by the $F_i$ vector, as in (2). $P_i$ is thereby power input from the grid to the hub and $T_i$ the feed-in of (e.g. renewable) power back to the grid from the hub’s output. $R_i$ are locally produced renewable energy and $L_i$, the present load. Since the concept favors a single flow direction (from left to right) through the coupling matrix $C_i$, the vectors $P_i$, $T_i$, $R_i$ and $L_i$ are larger or equal zero. In contrast, the storage input vectors might be negative as well, and all network layer related flows too.

$$
F_i = P_i - T_i
$$

Now it is possible to form the nodal equations, similar to Kirchhoff’s circuit laws, in (3). From [2] a nodal matrix $N_{ij}$ and a nodal vector $N_{ii}$ were established, for the internal ($i$ to $j$) and external ($i$ to $\mathcal{E}$) connections, as in (4).

$$
0 = F_i + \sum_j F_{ij} + F_w
$$

The network (4) equation and the transition equation (2) are the only equations needed for a network description and are capable of dealing even with energy conversion inside the nodal-layer (containing the network). Note that storage ability is implemented in the hub-layer only.

IV. GRID COSTS

When speaking of cost only a price per energy is assumed (e.g. GWh), since an annual basic price has no influence on an optimization unless an energy carrier would drop out completely. The nature of energy does not matter too, only the inherent energy density is used. The model simplifies all flows to a network with losses. Active power or any issues on grid stability in the electrical part is not investigated, as the intended application of the model is for long-term planning.

A. Modeling of Grid Costs

Considering the hub and node concept the new total grid costs $TGC$ can only appear at connections between nodes $F_{ij}$ or to the superior external grid $F_{in}$. Note that the flow from node to hub $F_i$ already contains two cost components. The inter-nodal costs $IC$ are therefore costs for an energy-carrying infrastructure. It depends on the application, the size of the hub’s dedicated area, if these grid costs appear within the transmission, sub-transmission or distribution level. A second term of costs $XC$ shall be employed for the external connections, except when an island grid operation is assumed.

$$
TGC = IC + XC
$$

The costs thereby incurred can be added in (7) to the existing costs for energy from the grid $TC$ and benefits from feed-in tariffs $TB$, which both together were labeled as total hub costs $THC$ in (6).

$$
THC = TC - TB
$$

$$
TSC = THC + TGC
$$

It is now the time to introduce the prices according to the new costs. As supplied before [2], all prices and benefits can be set for each hub independently. The same is realized for the grid costs, the prices are defined per line. From the consumers and for the optimizations taken point of view just the per delivered energy accumulated costs are of interest, thus (2) global costs are applied. Let $F_{in}$ be the price for internal and $F_{in}$ the price for external cost in (8). Due to the circumstance that $F_{ij}$ and $F_w$ can be negative, a case differentiation is necessary.

$$
IC = \sum_{i<j} F_{ij}^T \cdot F_{ij} \quad XC = \sum_i \Xi_i^T \cdot F_{in}
$$

with $F_{ij}^T = \begin{cases} F_{ij} & \text{if } F_{ij} \geq 0 \\ -F_{ij}/\eta & \text{if } F_{ij} < 0 \end{cases}$

and $F_{in}^T = \begin{cases} F_{in} & \text{if } F_{in} \geq 0 \\ -F_{in}/\eta & \text{if } F_{in} < 0 \end{cases}$

$$
THC = \sum_i \Psi_i^T \cdot P_i - \Phi_i^T \cdot T_i
$$

The well-known total hub costs in (9) are listed for completeness again. Obviously are (5) and (6) determining the total system costs $TSC$ in a new way to (10).

$$
TSC = \sum_i TSC_i(t)
$$

$$
= \sum_i \sum_{t=1}^i THC_i(t) + \sum_{t=1}^i TGC(t)
$$

$$
= \sum_i \sum_{t=1}^i (\Psi_i^T \cdot P_i - \Phi_i^T \cdot T_i)(t)
$$

+ $\sum_{t=1}^i \sum_{i<j} (F_{ij}^T \cdot F_{ij})(t) + \sum_{t=1}^i \sum_i (\Xi_i^T \cdot F_{in})(t)$

B. Optimization of Grid Costs

The costs of energy from the grid, the benefits of the feed-in (which are just negative costs), and the newly introduced grid costs are used as weighting factors for the optimization. The total system costs are a linear addition of all sub-costs
over all time steps. Inequality conditions as well as boundaries are part of the optimization as well, not shown here.

\[
\begin{align*}
\text{Minimize} & \quad \bar{z} (F_y, F_{\text{el}}, F_{\text{he}}, TSC) \\
\text{Subject to} & \quad (L + T_c) = C_i - (P + R_i) \\
& \quad F_y = P - T_i \\
& \quad F_{\text{el}} = N_y \cdot F_y - N_{\text{el}} \cdot F_{\text{el}} \\
& \quad TSC = THC + TGC \\
& \quad THC = TC - TB = f(\Psi, \Phi) \\
& \quad TGC = IC + XC = f(\Gamma, \Xi)
\end{align*}
\] (11)

C. Computational Aspects

When optimizing a network of nodes some problems may occur. The energy hub concept itself rests upon the idea of a complex interaction of different energy carriers, instead of just electricity. Any complexity found in the simulations is a tribute to certain qualities. Our network is an open system, since at least the coupling matrix \(C\) has in practice thermodynamic losses. The solution set of a network forms a high-dimensional hyperspace, which is quite non-linear due to the large number of variables. Even the elementary example of a network with two nodes, as in Fig. 2, has five distinct unknowns per energy carrier. With the number of nodes rising, the number of connections \(F_y\) grows even faster, as energy networks are meshed or looped. Additionally, the consideration of losses in the grid, as in (8), yields to discontinuities in the hyperspace, at a number of one per connection. It is self-evident that from a certain number of nodes the individual cases cannot be optimized separately, due to their interdependency.

The complexity is of course steadily growing when introducing storage in the network. Nevertheless, it has been approved that standard optimization algorithms are capable to solve the problem.

V. GRID COST APPLICATION

A. Description of example model

The next step is the implementation of a realistic scenario of the grid costs optimization in conjunction with energy storage and lossy network. The network model, shown in Fig. 5, consists of four nodes with two energy carriers, electricity and heat.

![Network example with four nodes, four hubs and two external connections](image)

Both \(S_2\) and \(S_3\) locally produce energies and have the possibility to store in batteries. \(S_2\) produces and stores heat and \(S_3\) stores electricity. All \(S_1, S_2\) and \(S_3\) have heat pumps, among two of them, \(S_1\) and \(S_3\), have loads, electricity load for \(S_1\) and heat load for \(S_3\). \(S_1\) and \(S_3\) have external connections from where they each possibly get electricity and heat. The configuration of hubs is described in Table 1 in the appendix. In this network model, \(F_{12}\) and \(F_{13}\) exchanges both electricity and heat, \(F_{14}\) exchanges only electricity and \(F_{23}\) exchanges only heat. Since this example takes losses into consideration, this relationship naturally yields to nodal matrices, as in (12). Detailed explanation about nodal matrix appears in [2]. Note that the nodal matrix \(N_y\) has always skew-symmetric entries and the main diagonal is zero.

\[
\begin{align*}
N^d_{y} &= \begin{bmatrix} 0 & -1 & -1 & -1 \\ n_{21} & 0 & 0 & 0 \\ n_{31} & 0 & 0 & 0 \\ n_{41} & 0 & 0 & 0 \end{bmatrix} \\
N^e_{y} &= \begin{bmatrix} 0 & -1 & -1 & 0 \\ n_{21} & 0 & -1 & 0 \\ n_{31} & n_{32} & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\] (12)

The focus of this trial lies on how \(S_2\) achieves heat load. \(S_2\) has many candidates for an energy provider; heat storage of \(S_2\), \(X\) and \(S_3\). \(S_2\) would choose an adequate source according to the configuration of grid costs. For example, if both prices \(X\) and \(R_{el}\) are higher than both of heat grid prices, through comparison of \(X\) and \(R_{el}\), \(S_2\) takes heat from less expensive connection, either \(X\) or \(R_{el}\). If all external grid prices, \(X\) and \(R_{el}\), are higher than internal grid prices, optimization would force the network to resolve loads internally. By measuring price of \(R_{el}\) against \(R_{el}\), \(S_2\) takes energy from \(S_3\) or from \(R_{el}\) of \(S_3\). If \(R_{el}\) is cheaper than \(R_{el}\), \(S_2\) produce heat from electricity provided by \(S_2\) with its heat pump. Also, for \(S_2\) there are two providers of electricity; \(X\) and \(R_{el}\) belongs to \(S_2\). By keeping many alternatives this network effectively presents realistic behavior of network flow according to the configuration of grid prices.

The simulation is done with MATLAB. The optimization runs with the predefined MATLAB function fmincon that is minimizing an object function under linear and non-linear constraints. In order to present relational behavior of network flow, we simulated three settings taking storage and lossy network into account. Table 2 in the appendix shows grid prices we used in this simulation. In order to effectively show the influence of grid cost, this example ignores the day tariff of energy carriers. Electricity and heat have equal and small values in \(\Psi\) vectors.

B. Optimization result

As mentioned earlier, the main purpose of this application is looking into the influence of grid costs by observing how energy is transmitted to \(S_2\) for heat load shown in Fig 8. To effectively achieve this goal, various settings have been applied in addition to predefined theories such as energy storage and lossy network. Consequently, Fig. 6 presents results of setting A, B, C according to different trans-
mission efficiency, a) and b) with $\eta = 0.99$, c) and d) with $\eta = 0.3$, while impact of storage appears in Fig. 7.

In the result of simulation with $\eta = 0.99$, in the setting A, electricity is taken from external to $\delta_2$ via $\delta_1$ and the energy is transferred with a form of electricity over heat since $\Xi_{el}$ is the cheapest and $\Gamma_{el}$ is the cheaper than $\Gamma_{he}$. In the setting B, although $\Xi_{el}$ is the cheapest, heat is transferred from $\delta_3$. Because sending electricity from external grid makes surcharge in addition to heat transmission price which is necessarily imposed in both cases. Losses during transfer are also considered. On the contrary in the last setting, in spite of additional charge, electricity is transmitted from $\delta_3$ to $\delta_2$ via $\delta_1$, instead of directly taking heat from $\delta_3$. This process is made since $\Gamma_{he}$ is still more costly despite the additional transmission of electricity.

From Fig. 6, result with $\eta = 0.3$, an obvious change is easily noticed such as more energy transmission caused by huge losses. Moreover in the setting B, heat is transmitted from $\delta_1$ to $\delta_2$ which does not exist in previous case. That transition starts when heat storage is all used up. Therefore $\delta_1$ needs to receive energy from external grid, which is the second cheapest alternative via $\delta_1$. Regardless of cheap price of $\Xi_{el}$, $\Gamma_{el}$ is much more expensive than $\Gamma_{he}$. To optimize $TSC$, $\delta_2$ transforms electricity into heat and transmits it to $\delta_3$. Other noticeable change appears in setting C. Because of non-negligible losses during the energy transmission, $\delta_1$ prefers to take heat from heat storage belonging to $\delta_2$ than using indirect transmission of electricity.

It is now the time to see the impact of presence of storage on $TSC$ in consideration of grid cost. Without storage, in spite of supply of renewable $\mathbf{R}_i$, at certain point of time step the local $\mathbf{R}_i$ at certain point of time step the local $\mathbf{R}_i$ is insufficient to satisfy local demand $\mathbf{L}_i$ because of the day tariff of $\mathbf{R}_i$. Therefore even if external grid costs are a lot more expensive than internal grid costs, network is forced to get energy from external connection and that action causes high cost.

On the other hand, at a certain point of time step $\mathbf{R}_i$ is more than sufficient to supply load demand. When $\mathbf{R}_i$ is more than loads, the energy left in the storage should be used up according to the equality condition of optimization as shown in (11). As a result, additional transfer is conducted imposing noticeable expenses. In this application, the latter has bigger influence on $TSC$ than the former that leads to shape of $TSC$ resembles $\mathbf{R}_i$, not the opposite shape of $\mathbf{R}_i$.

Since the absolute value of all powers and costs in the figures is arbitrary and explanatory only, the values are
given in per units (pu) and monetary units (mu). Prices therefore are implicitly given as monetary units per units (mu/pu). Each setting represents a day of 96 time steps.

VI. CONCLUSION

The existing concept of multi-energy optimization regards prices for the energy carriers as well as benefits from feed-in of renewable power to the grid. Expanding the optimization to grid-based costs is carried out on the previously developed network flow theory. Two prices are utilized by the introduction of grid internal $IC_i$, external costs $XC_i$ and the corresponding total grid costs $TGC_i$. $\xi_i$ is a representation of external prices, e.g. from cross-border auctions or other transmission grids, and $\Gamma_i$ involves local grid costs.

With special focus on the pricing of multi-energy network flow, the integration of grid cost is derived, and illustrated within an example. By assigning different grid prices, with various settings such as with and without storage, with different transmission efficiency, the power flow in network becomes better apparent.

ACKNOWLEDGMENT

The authors would like to thank the Regionalwerke AG Baden and the Agency of Energy - City of Baden for the prosperous cooperation. Also a special thank goes to ABB, Areva, Siemens and the Swiss Federal Office of Energy for their contribution to the VoFEN project, and finally to all group members and Prof. K. Fröhlich.

APPENDIX

TABLE 1: Configuration of Hubs

<table>
<thead>
<tr>
<th>Location</th>
<th>Conversion</th>
<th>Input/Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub 1</td>
<td>el $\rightarrow$ el</td>
<td>$\mathbf{I}_e$</td>
</tr>
<tr>
<td></td>
<td>el $\rightarrow$ he</td>
<td>$\mathbf{I}_h$</td>
</tr>
<tr>
<td>Hub 2</td>
<td>el $\rightarrow$ he</td>
<td>$\mathbf{R}_h$</td>
</tr>
<tr>
<td></td>
<td>he $\rightarrow$ he</td>
<td>$\mathbf{R}_h$</td>
</tr>
<tr>
<td>Hub 3</td>
<td>el $\rightarrow$ he</td>
<td>Heat storage</td>
</tr>
<tr>
<td></td>
<td>he $\rightarrow$ he</td>
<td>Heat storage</td>
</tr>
<tr>
<td>Hub 4</td>
<td>El $\rightarrow$ el</td>
<td>Electricity storage</td>
</tr>
</tbody>
</table>

TABLE 2: Three settings of prices (mu/pu)

<table>
<thead>
<tr>
<th>Setting</th>
<th>$\Psi_e$</th>
<th>$\Psi_h$</th>
<th>$\xi_e$</th>
<th>$\xi_h$</th>
<th>$\Gamma_e$</th>
<th>$\Gamma_h$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>4.0</td>
<td>0.3</td>
<td>4.0</td>
</tr>
<tr>
<td>B</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>4.0</td>
<td>4.0</td>
<td>0.3</td>
</tr>
<tr>
<td>C</td>
<td>0.3</td>
<td>0.3</td>
<td>4.0</td>
<td>4.0</td>
<td>0.67</td>
<td>1.83</td>
</tr>
</tbody>
</table>

REFERENCES