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Optimal Power Dispatch in Multi Carrier Energy System Using Visual C++

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***Abstract*-- Energy has always been critical for economic growth and social development. As economies develop, energy consumption grows more or less in parallel. An adequate and affordable energy supply is needed to meet the demands of industrial, commercial and domestic users and to enable the movement of people and goods. In order to supply the energy that the region needs for future economic growth and to reduce the large portion of its population without access to modern energy supplies will require a substantial increase in the size and diversification of energy infrastructure. The need for developing energy alternatives & their better use is thus evident. The consideration of multiple energy carriers, not only electricity, but it is believed that synergies among various forms of energy represent a great opportunity for system improvements. This paper presents generic framework for steady-state modeling and optimization of energy systems including multiple energy carriers. The general system model includes conversion and transmission of various energy carriers. The couplings between the different infrastructures are explicitly taken into account based on the concept of "energy hubs". For determining the optimal system operation, multi-carrier optimal dispatch approach is developed. A general optimality condition for optimal power dispatch of multiple energy carriers is derived and results can be compared to get the most optimal values of different powers & hence hub marginal cost (HMC) & system marginal cost (SMC) is calculated for a given system & loads. A multi carrier cost calculator is developed by using Visual C++ in order to increase the speed of calculations & accuracy.**

***Index Terms*—Energy Infrastructures, Multiple Carrier Energy System, Energy Hub, Energy Interconnector, Energy Hub Systems, Optimal Power Dispatch, Hub Marginal Cost (HMC), System Marginal Cost (SMC) etc.**

I. Introduction

Most of today's energy infrastructures evolved during the second half of the twentieth century, and it is questionable if they meet the requirements of tomorrow. The major sources of commercial energy in India are coal & oil. Besides congested transmission systems, many facilities are approaching the end of their prospected lifetime. In addition, other issues such as the continuously growing demand for energy, the dependency on limited fossil energy resources, the restructuring of power industries, and the general aim of utilizing more sustainable and environmental friendly energy sources raise the question of whether piecewise changes of the existing systems are sufficient to cope with all these challenges [31].

In the past, common energy infrastructures such as electricity and natural gas systems were mostly planned and operatedindependently. Motivated by different reasons, a number of recent publications suggest an integrated view of energy systems including multiple energy carriers, instead of focusing on a single energy carrier. One incentive for that is given by the increasing utilization of gas-fired distributed generation, especially co- and trigeneration. The conversion of energy between different carriers establishes a coupling of the corresponding power flows resulting in system interactions. The investigation of such phenomena requires the development of tools for an integrated analysis of multiple energy carrier systems, which has become a recent field of research [9].

Table.1: Assessment of different fuel reserves in India at the end of 2012

Fuel	Reserves	Expected Life (R/P Ratio)
Coal	60600 Million tones	100
Oil	5.7 Thousand Million Barrels	17.5
Natural Gas	1.3 Trillion Cubic meters	33.1

The consideration of multiple energy carriers, not only electricity, but it is believed that synergies among various forms of energy represent a great opportunity for system improvements. Besides the possibilities of modern information technology, state-of-the-art as well as emerging and looming energy technologies, e.g. fuel cells, are taken into account. The time horizon for implementation is set to 30 to 50 years from now. Thus, the basic question to be answered is: "How should energy systems look like in 30 to 50 years, and what can be expected from them?" Figure 1 outlines this process [20].

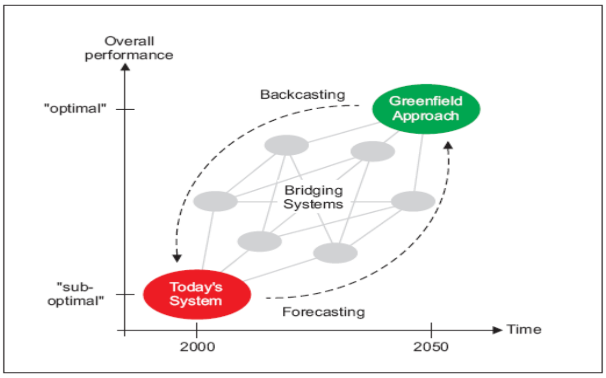

Figure 1: Greenfield Approach via bridging systems.

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II. COMBINING ENERGY INFRASTRUCTURES

Industrial, commercial, and residential consumers require various forms of energy services provided by different infrastructures. In the industrialized part of the world, coal, petroleum products, biomass, and grid-bound energy carriers such as electricity, natural gas, and district heating/cooling are typically used. So far, the different infrastructures are most often considered and operated independently.

Combining the systems can result in a number of benefits. Synergy effects among various energy carriers can be achieved by taking advantage of their specific virtues: Electricity, for example, can be transmitted over long distances with comparably low losses; chemical energy carriers such as natural gas can be stored employing relatively simple and cheap technology. With so-called line packing techniques compressible fluids can be stored in pipeline networks, even if there are no designated storage devices installed.

Combining the infrastructures means to couple them, thereby enabling exchange of power among them. Couplings are established by converter devices which transform energy into other forms. The question to be answered is of course where to put which devices and how to operate them. Therefore models and methods have been developed to find the optimal coupling and power exchange among multiple energy carriers based on various criteria such as cost, emissions, energy efficiency, availability, security, and other parameters [15, 29].

III. MULTIPLE CARRIER ENERGY SYSTEMS

In multiple carrier energy systems, i.e. energy system comprising not only electrical energy but also e.g. thermal & chemical energy etc. The interconnections between the different energy carriers results in benefits, in particular for reducing expected energy not supplied & in improving the overall system reliability. This is true for all the involved energy carriers as long as the ratings of the loads & all the installed components are similar. Otherwise, the systems with larger ratings improve the reliability however these systems do not benefit from the interconnections.

In general the infrastructure for the supply of electrical, chemical & thermal energy has been treated separately as these are supplied, maintained by individual industries & thus the topologies & operational strategies have been developed independently of one another. But now days the increasing development indicate an increasing mutual dependence & competition between these infrastructures. This trend is particularly driven by the increasing number of gas fired power stations, converting natural gas into electricity & thermal energy. Different technologies exist both for small scale & large scale applications & thus indicate the possible interdependencies of these energy carriers for transmission & distribution levels. The technology for small scale applications includes few kW suitable for small houses & offices etc. whereas the technology for small scale applications with up to several hundred MW of installed capacity is already well established through gas fired power stations, converting natural gas into electricity. Particularly Combined Cycle Gas Turbines (CCGT) plays a major role in this category. The technology of CCGTs allows building medium sized power stations that are at least as cost efficient as conventional thermal & hydro power stations with their large economies of scales. Gas fired power stations basically establish a coupling between the chemical & electrical infrastructures, resulting in a certain interchangeability & redundancy between these two energy carriers [17, 19, 21].

IV. ENERGY HUB

An energy hub is considered a unit where multiple energy carriers can be converted, conditioned, and stored. It represents an interface between different energy infrastructures and/or loads. Energy hubs consume power at their input ports connected to, e.g., electricity and natural gas infrastructures, and provide certain required energy services such as electricity, heating, cooling, and compressed air at the output ports. Within the hub, energy is converted and conditioned using, e.g., combined heat and power technology, transformers, power-electronic devices, compressors, heat exchangers, and other equipment. Real facilities that can be considered as energy hubs are, for example, industrial plants (steel works, paper mills), big building complexes (airports, hospitals, shopping malls), rural and urban districts, and small isolated systems (trains, ships, aircrafts etc.). Figure 2 shows an example of an energy hub.

Thus an energy hub is defined as an interface between energy producers, consumers, and the transportation infrastructure. An energy hub can be seen as a unit that provides the basic features input and output, conversion, and storage of different energy carriers. Loads and primary sources of energy (e.g. hydro, wind, solar) are considered to be connected to the hub.

From a system point of view, an energy hub can be identified as a unit that provides the basic features:

- input and output,
- conversion, and
- storage

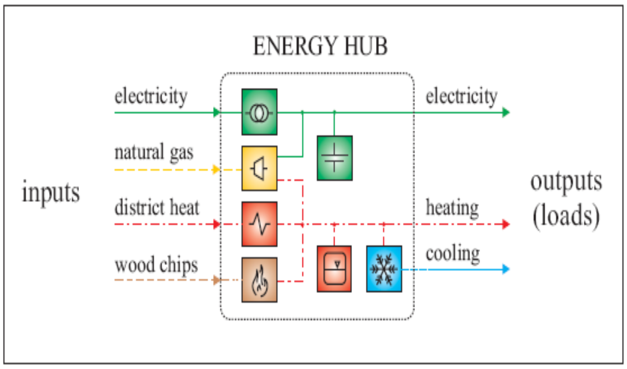

Figure 2: Example of an Energy Hub.

Energy carriers offered at the hub's input can be characterized based on their cost, related emissions, availability, and other criteria; the inputs can then be optimally dispatched based on these quantities. In addition, utilizing energy storage represents an opportunity for increasing the overall system performance; therefore, storage is already taken into account in the planning phase. Especially when energy sources with intermittent primary energy (e.g., wind, solar) are considered, storage becomes important since it enables affecting the corresponding power flows. Compensation of fluctuating power flows is possibly the most evident application of energy storage technology. However, investigations have shown that storage can be utilized in such a way that it positively affects all of the aforementioned criteria, especially when considering a liberalized market environment.

Originally, the energy hub approach was developed for Greenfield design studies. Models for integrated analysis of energy and transportation systems employing the energy hub concept. The energy hub idea was also picked up by a municipal utility in Switzerland, the Regionalwerke AG Baden, which plans to build an energy hub containing wood chip gasification and methanation, and a cogeneration plant. Figure 3 sketch the basic layout of this hub [15, 18, 20].

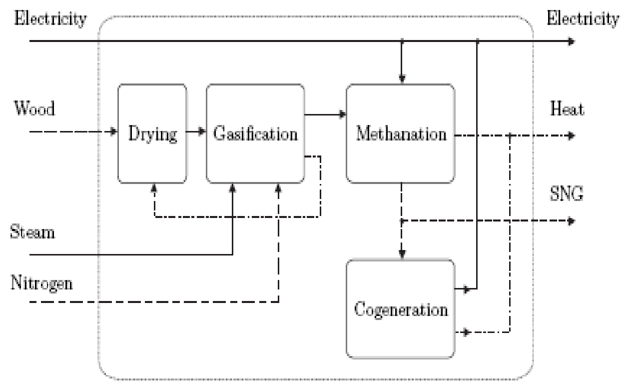

Figure 3: Sketch of the Energy Hub by Regionalwerke AG Baden, Switzerland.

V. THE INTERCONNECTOR CONCEPT

Integrating different energy carriers is also possible in terms of transmission. Thus a device named *energy interconnector* is proposed and that enables integrated transportation of electrical, chemical, and thermal energy in one underground device. So far, the most promising layout seems to be a hollow electrical conductor carrying a gaseous medium inside, as shown in Figure 4 [15].

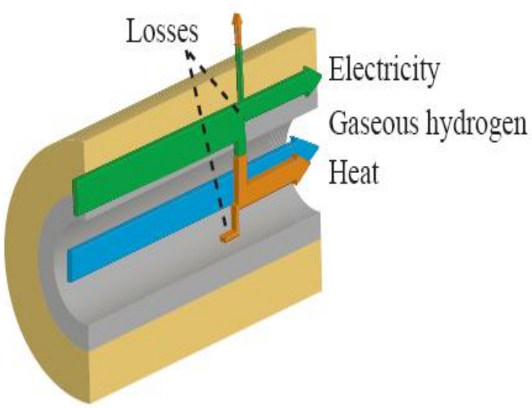

Figure 4: Possible layout of an Energy Interconnector.

VI. ENERGY HUB SYSTEMS

In regard to energy hubs, the whole energy supply infrastructure can be considered as a system of interconnected energy hubs. Figure 5 shows three energy hubs interconnected by electricity and natural gas networks. This is an example for the supply of a town that is roughly divided into three areas: industrial, commercial, and private/residential. Each area is interfaced with natural gas and electricity distribution networks via an energy hub. The internal layout of the hubs is adapted to the specific load requirements.

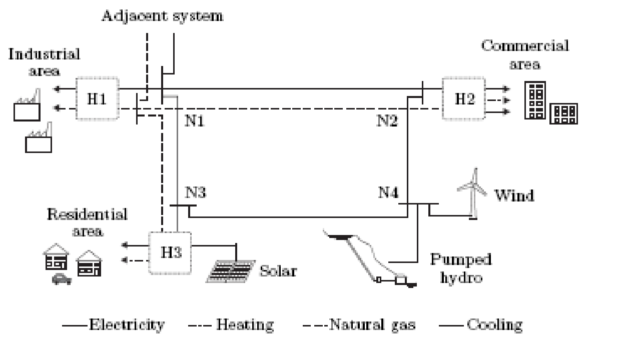

Figure 5: Sketch of a system of Interconnected Energy Hubs.

The system is supplied via adjacent networks, a photovoltaic plant connected to hub H3, and wind and hydro plants connected to the electricity network via node N4. This node could represent a more remote station outside the town where hydro reservoirs are available. Concerning energy transmission between the hubs, it should be noted that the combination of different energy carriers in integrated transmission devices is subject to research [14].

VII. OPTIMAL POWER DISPATCH

In common electricity economic dispatch problems, network losses are included in the equality constraint which accounts for conservation of power. A general dispatch rule can then be derived by introducing penalty factors, which include sensitivities between transmission losses and generator powers. For electrical AC networks, penalty factors can be computed using bus voltage angles as intermediaries.

Figure 6 shows the equivalent electrical & multiple carrier energy system optimal power dispatch [2, 13]. There are a number of reasonable objectives which can be used in economic dispatch procedures Figure 7 shows the test system of three interconnected energy hubs using electricity, natural gas & district heat at the input terminals of each hub & electricity & heat at the output terminals.

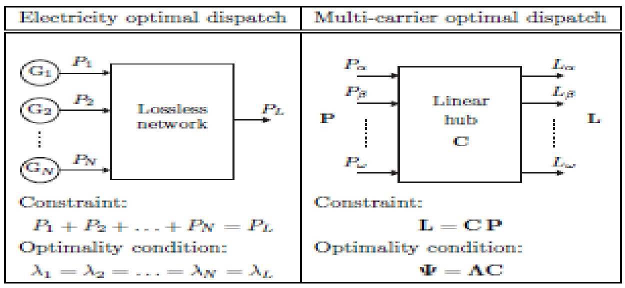

Figure 6: Electricity and Multi-Carrier Optimal Power Dispatch.

We consider a linear energy hub as shown in Figure 8. The hub contains a direct connection to the electricity network (assumed lossless), a combined heat and power (CHP) plant and a heat exchanger (HE) which connects the load with the heating infrastructure. Electricity and heat loads can be met by directly consuming the required power from the corresponding networks or by generating part (or all) of the load power with the CHP.

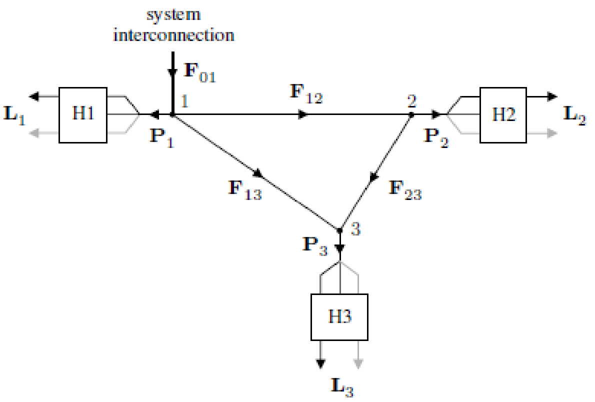

Figure 7: Test system of three Interconnected Energy Hubs.

The power flows connection is assumed to be lossless through the hub should be optimized for a specific snapshot of the load aiming at minimal energy cost. Figure 8 shows the independent networks for electrical & natural gas supply

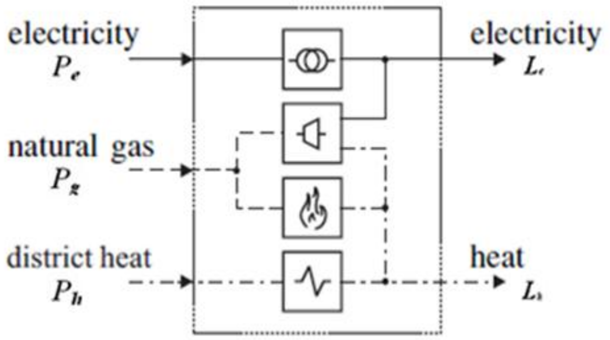

Figure 8: Energy Hub with Combined Heat & Power (CHP) Plant & Heat Exchanger.

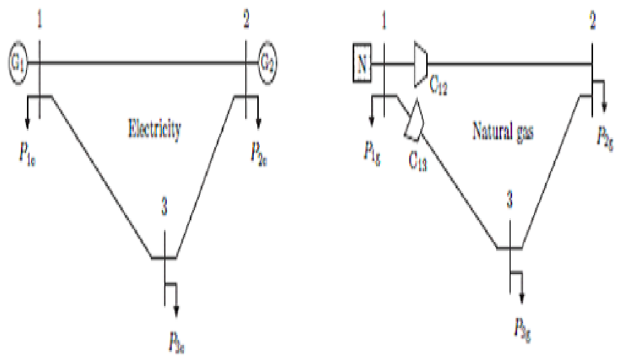

Figure 8: Independent Electrical & Natural Gas Networks.

The main aim is to obtain the mathematical model of the given system (Energy Hub) in terms of its parameters such as efficiencies (CHP & HE), powers *(P_e, P_g & P_h)* & dispatch factors. The different efficiencies such as from gas to electricity η_{ge}^{CHP}, from gas to heat η_{gh}^{CHP}, from heat to heat η_{hh}^{HH} & the load vectors L_e & L_h are assigned different values. The mathematical treatment will give us simultaneous equations & their solutions will give us the optimal values of powers *(P_e, P_g & P_h)* which will give us the optimal values of hub marginal cost Λ (HMC) & system marginal cost Ψ (SMC). The same method can be repeated for different values of the parameters mentioned above & the results can be compared to get the minimal value for optimal power dispatch.

VIII. RESULTS & DISCUSSION

We will derive the converter coupling matrix for the energy hub shown in Figure 7, which consumes electricity, natural gas, and district heat, and delivers transformed electricity and heat. We assign the electricity, natural gas, and district heat input powers as P_e, P_g, *and* P_h, and the electricity and heat output powers as L_e and L_h, respectively. These are the entries of input and output vectors. For the sake of simplicity, we assume constant efficiencies of the converter devices: η_{ee}^{T} for the transformer, η_{ge}^{GT} and η_{gh}^{GH} for the gas turbine, η_{gh}^{F} for the furnace and η_{hh}^{HE} for the heat exchanger. The power output of the hub results in the following equations:

$$L_e = \eta_{ee}^{T} P_e + v\eta_{ge}^{GT} P_g$$

$$L_h = v\eta_{ge}^{GT} P_g + (1 - v)\, \eta_{gh}^{F} P_g + \eta_{hh}^{HE} P_h$$

In terms of matrix form it can be written as:

$$\begin{bmatrix} L_e \\ L_h \end{bmatrix} = \begin{bmatrix} \eta_{ee}^{T} & v\eta_{ge}^{GT} & 0 \\ 0 & v\eta_{gh}^{GT} + (1-v)\eta_{gh}^{F} & \eta_{hh}^{HE} \end{bmatrix} \begin{bmatrix} P_e \\ P_g \\ P_h \end{bmatrix}$$

For the test system under consideration containing linear energy hubs having direct connection to the electricity network (assumed lossless), a combined heat and power (CHP) plant and a heat exchanger (HE) which connects the load with the heating infrastructure the required loads are given with:

L_e = 2 p.u. & L_h = 5 p.u.

The CHP is assumed to operate with constant efficiencies as:

η_{ge}^{CHP} = 0.3 (gas-electricity)

η_{gh}^{CHP} = 0.4 (gas-heat)

η_{hh}^{HH} = 0.9 (heat exchanger)

We assume an objective function that reflects the total energy cost for the hub in the time period considered in monetary units (mu), where costs of the individual energy carriers are modeled as quadratic functions of the corresponding powers in per units (p.u.):

$$TC = \sum_{\alpha=e,g,h} (a_\alpha P_\alpha + b_\alpha P_\alpha^2)$$

Here we aim at minimizing total energy cost for the whole system considered. The coefficients a_α and b_α assumed for this example and are given in Table 1.

Table.2: Different values of Loss Coefficients.

Carrier (α)	**a_α in mu / pu**	**b_α in mu / pu^2**
Electricity (e)	12	0.12
Natural Gas (g)	5	0.05
Heat (h)	4	0.04

The matrix ***C*** which can be derived from the converter efficiencies and the topology of the hub.

$$C = \begin{bmatrix} C_{ee} & C_{ge} & C_{he} \\ C_{eh} & C_{gh} & C_{hh} \end{bmatrix} = \begin{bmatrix} 1 & 0.3 & 0 \\ 0 & 0.4 & 0.9 \end{bmatrix}$$

As per the well established dispatch rule which also includes the vector of system marginal objectives, in this case system marginal cost (SMC) is denoted by **Ψ**. Its elements $\boldsymbol{\Psi_\alpha}$ can be calculated as the partial derivatives of the total cost TC with respect to the input powers P_α:

$$\Psi_\alpha = \frac{\partial TC}{\partial P_\alpha} = a_\alpha + 2b_\alpha P_\alpha$$

This will give us the optimal values of P_e, P_g & P_h:

$P_e = 0.429$ pu, $P_g = 5.235$pu, $P_h = 3.228$pu

And the values of Λ_e & Λ_h as:

$\Lambda_e = 12.103$ mu/pu & $\Lambda_h = 4.731$ mu/pu

Λ contains the hub marginal cost (HMC) for electricity and heat appearing at the output side of the hub. The marginal cost at the input side of the hub, the system marginal cost (SMC), can be calculated from the results.

$$\Psi = \begin{bmatrix} 12.103 & 5.524 & 4.258 \end{bmatrix} \text{ m.u./p.u.}$$

It can be observed that the marginal cost of heat increase between the input and the output of the hub from 4.258 to 4.732 mu/pu, which origins from 10% losses in the heat exchanger (η_{hh}^{HH} = 0.9). The marginal costs of electricity are equal on both sides of the hub since the connection is assumed to be lossless. Different investigations can be carried out using the presented combined optimal power dispatch approach. We focus on the system performance depending on the minimizing the total energy cost (TC) of the energy hubs of the system under consideration. Although the system considered in this example is quite small, the numerical method used comes to its limits under certain circumstances. Large systems have not been implemented yet, but from experience with smaller test systems, computational difficulties might be expected for realistically sized problems. For the analysis of large systems, linearized power flow models could be used as an alternative approach.

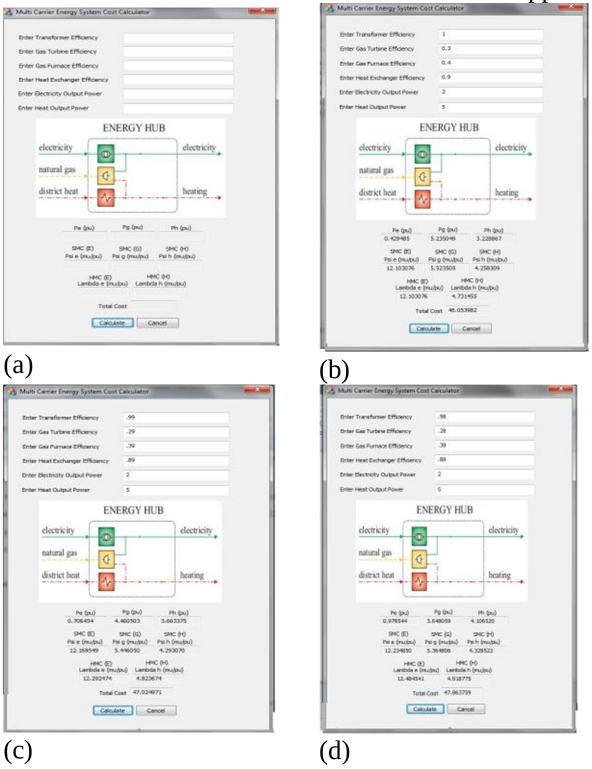

Figure 9: (a) Multi Carrier Cost Calculator (b), (c) & (d) Calculations of Cost with different values of efficiencies

IX. CONCLUSIONS AND FUTURE SCOPE

The main conclusions that can be drawn so far are as follows:

- The energy hub concept enables new design approaches for multiple energy carrier systems.
- The flexible combination of different energy carriers using conversion and storage technology offers a powerful approach for various system improvements. Energy cost and system emissions can be reduced, security and availability of supply can be increased, congestion can be released, and overall energy efficiency can be improved.
- The developed modeling and analysis framework provides suitable tools for the planning and operation of multiple energy carrier systems.

Future work includes the development of dynamic modeling and analysis tools (e.g., for evaluating stability), and the control of a system of interconnected energy hubs (centralized versus decentralized, agent-based). The concepts will be further refined and elaborated in more detail using realistic examples and case studies. There are a number of potential applications for the presented method. Besides electricity & natural gas which are commercially available, we can also include other modern non conventional sources of energy such as wind energy, photovoltaic using solar energy, fuel cells etc. if available depending upon the cost criterion. We can also include the storage elements for different energy carriers which will store their respective energy & that energy will be available for the future use. This will also involve modeling & optimization with more complex equations & their calculations. Besides applying recent developments to real problems, future work could include the following subjects:

- Dynamic phenomena and stability of multi-carrier systems.
- Hub communication, information exchange, ancillary services, and consumer services.
- Optimal control of multi-carrier systems, which can be considered "systems integrating logic, dynamics, and constraints".

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