ISSN : 0974 - 7435 Volume 8 Issue 6

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 8(6), 2013 [848-854]

A modeling and optimization approach for multi-carrier energy system considering the interaction between energy, product and emission

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ABSTRACT

The optimization problem of multi-carrier energy system has attracted considerable attention of worldwide researchers and engineers. It is well known that there exists a complex coupling relationship between energy, product and emission which has a significant impact on the performance of multi-carrier energy. In this respective, an "Integrated Hub" concept is developed which synthetically consider the interaction between energy, product and emission. Based on the proposed integrated hub structure, the network model for multi-carrier energy system is built and furthermore the mathematical formulation for optimization of this system is described in detail. An example case is illustrated to verify the performance and capability of the proposed approach.

KEYWORDS

Multi-carrier energy system;
Modelling;
Optimization;
Product;
Emission.

INTRODUCTION

With the rapid development of co-generation and tri-generation technologies, the traditional energy system evolves toward so-called multi-carrier energy system characterized by interconnecting different energy types including electricity, natural gas, coal, oil, biomass and other possible energy resource. In multi-carrier energy system, various energy carriers act mutually and may be converted from one type to another. For example, using CHP (Combined Heat and Power), it is possible to produce electricity and heat simultaneously out of natural and biogas. Due to the complex interaction between different energy carriers, the modeling and optimization problem for multi-carrier energy system has attracted considerable attention of worldwide researchers and engineers nowadays and a number of novel concepts have been developed such as basic units[1], micro grids[2], hybrid energy hub[3], energy hub[4] etc. Among them, the energy hub concept arise enormous interest and the further research work is carried out. By using energy hub, a number of aspects of energy system are analyzed and discussed (e.g., maximizing exergy efficiency[5], pricing of multi-energy network flow[6], predictive control[7], CHP optimized selection[8], modeling and optimization of renewable[9] etc).

It is well known that energy system is the important part of the society system which closely relates to economic and environmental system. Other than the coupling relationship between different energy carriers, energy system has a complicated interaction with product and emission. A variety of energy activities such as exploitation, storage, transmission, conversion, distribution and consumption are performed for product manufacture and meanwhile a certain amount of emission may be released. In addition, based upon the emergency of renewable technologies (e.g., biomass generation, waste-heat recovery), the released emission or useless byproducts can be converted renewable energy resource. From this point of view, the optimization problem of energy system not only takes into account the interdependence of various energy carriers, but also has a high correlation with product manufacture and emission release. Thus it is necessary to facilitating the integration of product and emission aspects into multi-carrier energy system model in order to plan and dispatch energy resource much more scientifically and reasonably. In this paper, based on the extension of energy hub structure, the factors of product manufacture and emission release can be incorporated into multi-carrier energy system and hence a so-called integrated hub concept is developed which synthetically considers the interaction between energy, product and emission. By using the modeling schema of integrated hub, the network model for multi-carrier energy system is built which extends the energy analysis scope from the only inside of energy system toward to the interaction between energy, economical and environmental system. In order to optimize the proposed network model of multi-carrier system, the mathematical formulation for optimization is described in detail. At end, an example case is illustrated to verify the performance and capability of the proposed approach.

INTEGRATED HUB STRUCTURE

Integrated hub extends the performance of energy hub to include not only the various energy activities, but also product manufacture and emission release in such a way that waste or byproduct recovering can be considered effectively. Integrated hub can be considered a basic unit that synthesizes the performance of energy activity, product manufacture and emission recovery. Inside a generic integrated hub, energy carrier can be converted (e.g., gas turbine, gas-fired boiler, etc) or distributed (e.g., transformer, heat exchanger, etc) or stored (e.g., fuel cell, battery, gas tank, etc) in order to satisfy the energy consumption required by product manufacture during which a certain amount of emission may be released and consequently causes environmental pollution. With respect to emission management, integrated hub provides both solutions including cleaning emission via decarbonization, desulfurization, denitrification, etc on one hand and recovering emission or byproduct via the renewable technologies such as waste-heat reusing, biomass generation, etc on the other hand. Integrated hubs can serve as interface between the interaction of energy, product and emission. Integrated hub interconnects with different grid-bound energy carrier, for example electricity, natural gas, districted heat which are converted and/or conditioned in the hub. The generated energy is then consumed for product manufacture and the remainder energy can be transmitted back to energy carrier grid. Meanwhile the released emission can be controlled for environmentally compatible management or energy recovery. All the activities about energy conversion, products manufacture and emission controls are performed within integrated hubs. In this regard, the integrated hub concept has an attractive capability for depicting the complex coupling relationship between energy, product and emission and hence provides the means to analyze how this coupling relationship influences the performance of multi-carrier energy.

A simple example of integrated hub is shown in Figure 1.Energy carrier set, $H = \{e,n,h,...\}$ can be defined in which e, n and h represents electricity, natural gas and heat power respectively. Material/product set and emission set are also defined as $M = \{a,b,c,...\}$ and $E = \{s,t,...\}$ respectively in which different material/product or emission types are included. The index for integrated hub is stated as $N = \{1,2,3,...n\}$. In Figure 1 P_1^e, P_1^n and P_1^h respectively indicate the energy feed from each energy carrier infrastructure such as electricity, natural gas and heat power. P_1^n is then partitioned into two branches according to the proportion of λ_1^n and $1-\lambda_1^n$. One part is converted to electricity and heat simultaneously via gas turbine equipment and the other can be used to generate heat power via gas-fired boiler. The generated energy power is then supplied to satisfy the energy consumption demand for manufacturing product b and c, which are denoted by T_1^e and T_1^h respectively. Meanwhile the remainder energy T_1^e and T_1^h can be delivered back to energy carrier infrastructure for other hubs utilization. M_1^a refers to raw material that can be dispatched in accordance with λ_1^a for respectively manufacturing product M_1^b and M_1^c. During the product manufacture, the generated high-temperature byproducts or emission can be transmitted to heat exchanger for recovering the heating value contained in these industry wastes indicated by P_1^{rh}. For environmental consideration, the wasted emission W_1^s needs to be converted to the environmentally-compatible released type W_1^t via applying several control technologies such as decarburization, desulfurization, dentrification, etc. The conversion efficiency of a variety of equipments for energy generation, product manufacture and emission control are represented by η. S_1^{eb} and S_1^{hc} indicate energy intensity of processing equipment which respectively specifies the consumed amount of electricity and heat for manufacturing per unit product b and c. The heat recovery efficiency of processing equipment termed R_1^{eb} describes the availably recovered heat per unit electricity consumed for manufacturing product b. The release intensity of processing equipment denoted by ψ_1^{cs} specifies the amount of emission s in order to manufacture per unit product c.

According to the structure and function of integrated hub, the mathematical model can be achieved as follows which comprises three types of equations respectively specifying energy balance, material balance and emission balance.

Energy balance equations (1)

$$T_1^e + T_1^{eb} = P_1^e \eta_1^e + P_1^n \lambda_1^n \eta_1^{ne}$$

$$T_1^h + T_1^{hc} = P_1^n \lambda_1^n \eta_{1T}^{nh} + P_1^n (1-\lambda_1^n) \eta_{1B}^{nh} + P_1^{rh}$$

$$T_1^{eb} = Q_1^b S_1^{eb}, \quad T_1^{hc} = Q_1^c S_1^{hc}, \quad P_1^{rh} = T_1^{eb} R_1^{eb} \qquad \textbf{(1)}$$

Material balance equations (2):

$$M_1^b = M_1^a \lambda_1^a \eta_1^{ab}, \qquad M_1^c = M_1^a (1-\lambda_1^a) \eta_1^{ac} \qquad \textbf{(2)}$$

Emission balance equations (3)

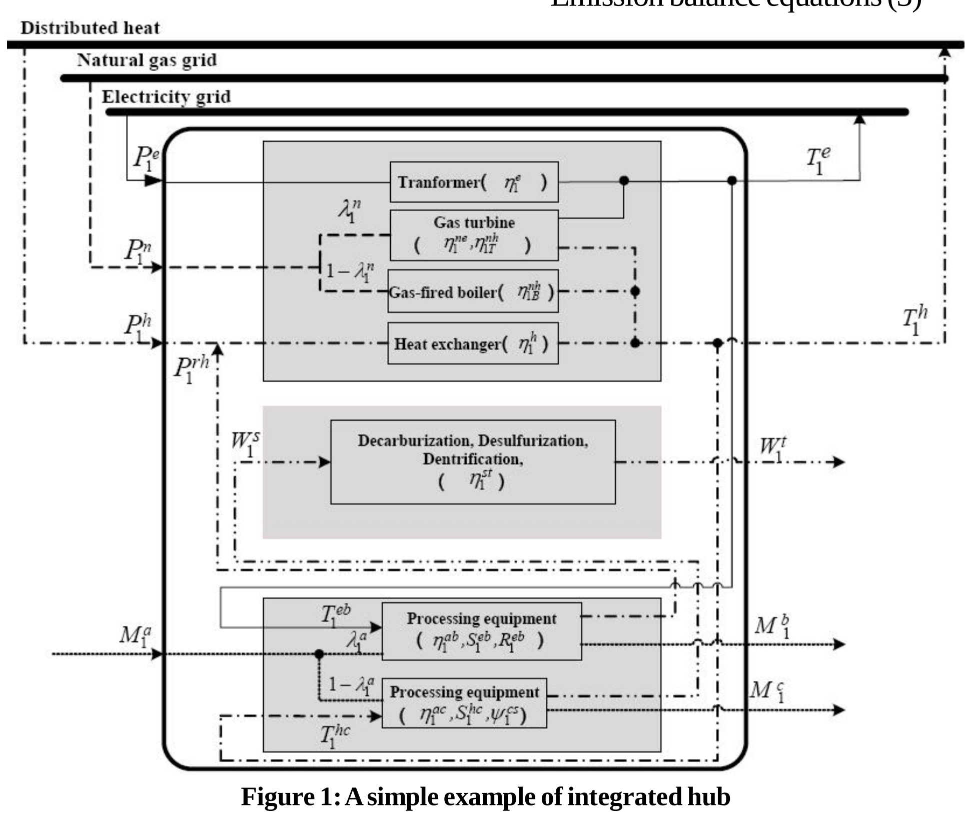

Figure 1: A simple example of integrated hub

$$W_1^s = M_1^c \psi_1^{cs} \ddot{y} \; W_1^t = W_1^s \eta_1^{st} \quad (3)$$

From the above equations, it can be seen that within the structure of integrated hub, energy, product and emission elements are interrelated closely and interact on each other in such a way that any change of one element may have a significant impact on the other two.

NETWORK MODEL FOR MULTI-CARRIER ENERGY SYSTEM

The network model for multi-carrier energy system can be established in the way that a number of integrated hubs are connected via different energy carrier infrastructure. Each integrated hub performs as a node in the network model and receives energy carrier from the grid-bound energy infrastructure, which can be converted or conditioned to the energy type demanded by local production, and meanwhile the remainder can be delivered back to energy infrastructure. In addition, integrated hubs are also connected each other because of the appropriate up-down-stream production chains including the recovery of byproducts. Note that the released emission is realistically processed locally and usually unnecessary to transport between different nodes.

With respect to the network framework of multi-carrier energy system, energy flow, material flow and emission flow equations can be formulated as the following, which specifies the input and output relationship between each node.

$$\sum_{i=1}^{n} P_i^{\alpha} = \sum_{i=1}^{n} T_i^{\alpha},\ \alpha \in H = \{e,n,h,\ldots\} \quad (4)$$

$$M_i^{\beta} = \sum_{j=1}^{m} M_j^{\beta},\ \beta \in M = \{a,b,c,\ldots\} \quad (5)$$

$$M_i^{\delta} = \sum_{j=1}^{m} M_j^{\delta},\ \delta \in E = \{s,t,\ldots\} \quad (6)$$

Equation (4) is energy flow formulation which indicates that for each particular energy carrier, the energy amount of injection to all the nodes from the infrastructure equals the whole remainder returning to the grid. Equation (5) is material flow equation stating that the products manufactured within upstream node i can be delivered to m number of downstream nodes acting as feedstock for the further production. Similarly, equation (6) indicates the flow of emission between upstream and downstream nodes.

MATHEMATICAL FORMULATION FOR OPTIMIZATION

Although the optimization of multi-carrier energy system correlates consumption cost, product profit, exploit availability, performance reliability, emission processing and other aspects which have different measurement basis, a unified optimal objective can be established from the economic perspective as shown in the following equation.

minimize

$$S = \sum_{\alpha \in H} \sum_{i \in N} P_i^{\alpha} C_P^{\alpha} + \sum_{\delta \in E} \sum_{i \in N} W_i^{\delta} C_W^{\delta} - \sum_{\alpha \in H} \sum_{i \in N} T_i^{\alpha} C_T^{\alpha} - \sum_{\beta \in M'} \sum_{i \in N} Q_i^{\beta} C_M^{\beta} \quad (7)$$

The optimal objective is to minimize cost portfolio S which is determined by cost of energy consumption (C_P^{α}) and cost of emission processing (C_W^{δ}) subtract revenue from feedback of the remainder energy power (C_T^{α}) and selling final product (C_M^{β}). Moreover, equations (1)-(6) constitute the constraints for optimization model.

CASE STUDY

In order to illustrate the proposed modeling approach, a case study can be provided as shown in Figure 2. Without loss of generality, the multi-carrier energy system is composed of four integrated hubs respectively connecting with different energy carrier infrastructure such as electricity, natural gas and distributed heat. For reasonably reducing the complexity of computation, all the generators in electricity grid can be concentrated to a single node denoted by **IH1** which is responsible for delivering electricity power to the grid. Natural gas is supplied freely meanwhile distributed heat is constrained in the scope of the system which means that none of any amount of heat can be obtained from the outside of the system. Each node can receive any energy carrier type and then convert or condition them for energy demand of local production and furthermore the remainder energy can be delivered back to energy infrastructure for other node use.

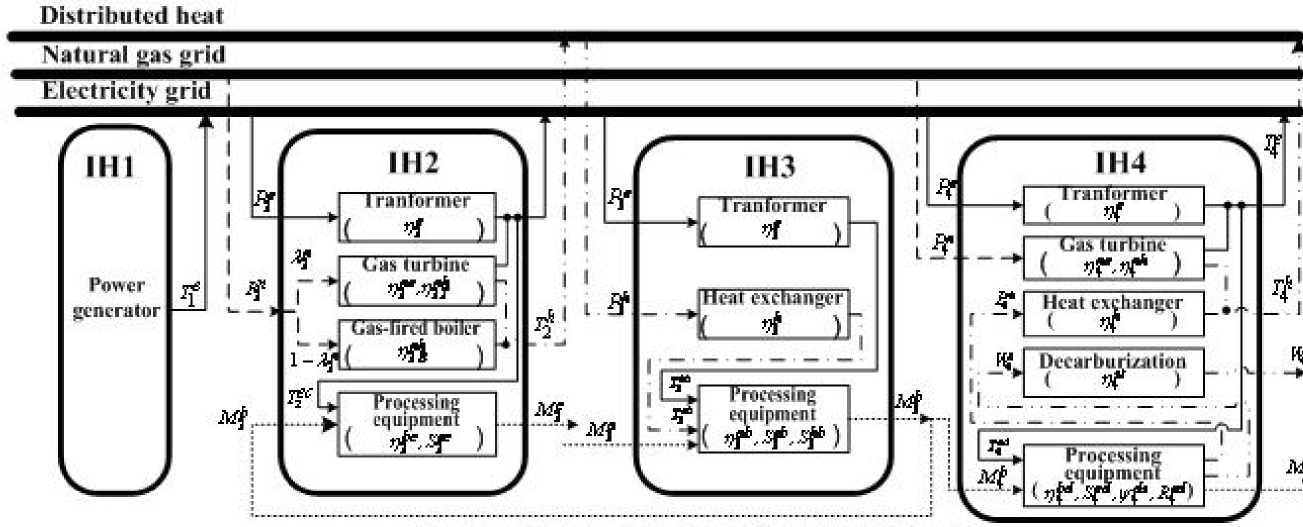

Fig.2 A case study composed of four integrated hubs

According to Equation (1)-(7), the optimization model of multi-carrier energy system described in Figure 2 can be achieved. The related model parameters defining the performance of individual integrated hub are specified in TABLE 1. Applying Matlab optimization toolbox, the simulation results can be obtained. For the convenience of description, all the parameters and variables are assumed dimensionless quantities.

which reaches the highest value, there exists and at other times there is. This situation can be clearly explained according to the impact of cost and profit on the optimal objective. When the value of is lower than 3.6*m.u /p.u.*, the product unit profit of node **IH4** is larger than that of node IH2 ( ) and moreover the product profit of node **IH4** plays a key role in the total cost calculation compared with its emission cost. Therefore, at time

TABLE 1 : The model parameters of case study illustrated (Per unit of energy: *p.u.*, Material and product unit: *m.p.u.*, Emission unit: *e.u.*, Monetary unit: *m.u.*).

IH2	IH3	IH4
$\eta_2^e = 0.62$, $\eta_2^{ne} = 0.64$ $\eta_{2T}^{nh} = 0.4$, $\eta_{2B}^{nh} = 0.8$ $\eta_2^{bc} = 0.65$ $S_2^{ec} = 0.34\ p.u./m.p.u$	$\eta_3^e = 0.62$, $\eta_3^h = 0.89$ $\eta_3^{ab} = 0.74$ $S_3^{eb} = 0.3\ p.u./m.p.u$ $S_3^{hb} = 0.42\ p.u./m.p.u.$	$\eta_4^e = 0.62$, $\eta_4^{ne} = 0.64$, $\eta_4^{nh} = 0.65$ $\eta_4^h = 0.89$, $\eta_4^{st} = 0.82$, $\eta_4^{bd} = 0.65$ $S_4^{ed} = 0.34\ p.u./m.p.u$ $\psi_4^{ds} = 0.43$ $R_4^{ed} = 0.12$
Unit cost	$C_P^n = 2.74\,m.u./p.u.$ $C_P^e = 3.67\,m.u./p.u.$ $C_W^t = 1.23\,m.u./m.p.u$	
Unit profit	$C_M^c = 2.16\,m.u./m.p.u.$ $C_M^d = 2.48\,m.u./m.p.u.$ $C_T^e = 3.67\,m.u./p.u.$ $C_T^h = 3.67\,m.u./p.u.$	
Raw material amount	$M_3^a = 34.6m.p.u$	

Considering the impact of the unit cost of electricity on the optimization results, is assumed to fluctuate during the periods of 24 weeks and the related optimization results can be obtained as illustrated in Figure 3.

From the results it is notable that the total cost S varies similarly with the fluctuation of C_P^e throughout the periods, which indicates thatis affected by greatly. In the interval between the 12th week and 16th week during except for 12th-16th weeks, compared with energy consumption cost, the product profit has a greater contribution to the total cost and it is suggested to apply all the raw material to produce productfor the cost minimization. On the other hand, when, i.e. at time between the 12th-16th weeks, the electricity consumption cost becomes the prime factor influencing the total cost and it is appreciated for node **IH4** to deliver more surplus

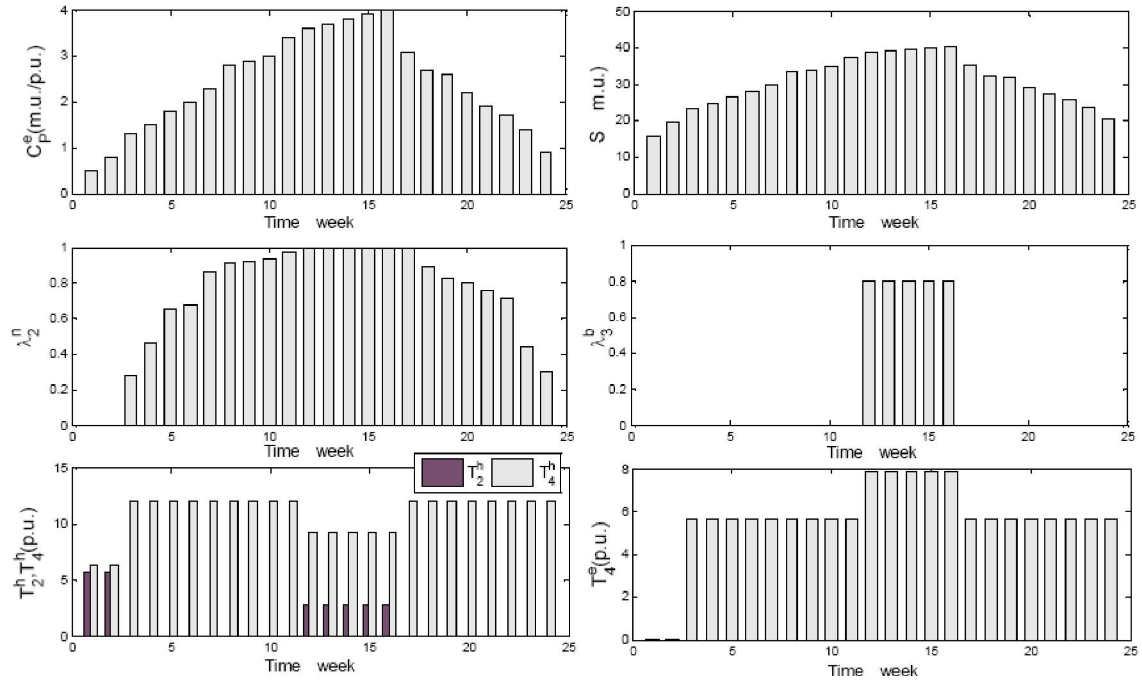

Figure 3 : The optimization results

electricity to the grid in order to offset the effect of higher electricity unit cost on.

From the variation of it can be indicated that when, the consumed electricity in node **IH4** is mainly supplied by the grid and with the electricity unit cost increasing, node **IH4** begins to use natural gas to generate electricity to satisfy the local energy demand and simultaneously deliver the surplus one to the grid. For example, at time during the 12th-14th week, the surplus amount of electrify delivered to the grid increases substantially. The similar situation occurs on where the variation trend of this variable is basically consistent with. With the electricity unit cost increasing it is suggested for node **IH2** to increase generation capacity of gas turbine and then supply electric power to the grid for offsetting the grid power cost.

Due to none of any amount of heat can be obtained from the outside of the system, the heat need required by node **IH3** is mainly supplied by the heat capacity of both node **IH2** and **IH4**. According to the variation of and, it can be seen that the heat generation substantially relies on node **IH4**. In addition, during the periods of the first two weeks and between 12th- 16th week, in order to realize the total cost reduction, on the premise of self-sufficiency in electricity generation demanded by local production as well as the benefit produced from the surplus electric power, node **IH4** supplies the heat power required by node **IH3** of which the shortfall one can be made up by node **IH2**.

CONCLUSION

Considering the complex coupling relationship between energy, product and emission, an “Integrated Hub” concept as well as the modeling framework for multi-carrier energy system based on it are developed characterized by synthetically consider the interaction between energy, product and emission. The application of developed model to a case study illustrates that the performance of energy system is closely correlated with product and emission.

ACKNOWLEDGEMENT

Their research work is supported by Chinese Nature Science Foundation Project (71273188, 91024131, and 91024023) and Information Development Project of Shanghai.

REFERENCES

[1] I.Bouwmans, K.Hemmes; Optimising energy systems-hydrogen and distributed generation, in Proc., 2nd Int.Symp. Distributed Generation: Power Sys-

FULL PAPER

tem Market Aspects, Stockholm, Sweden, **(2002)**.

[2] R.H.Lasseter, P.Piagi; Microgrid:a conceptual solution, in Proc., IEEE 35th, Annu.Power Electronics Specialists Conf., Aachen, Germany, 4285-4290 **(2004)**.

[3] R.Frik, P.Favre-Perrod; Proposal for a multifunctional energy bus and its interlink with generation and consumption, diploma thesis, Power Systems and High Voltage Laboratories, ETH, Zurich, Switzerland, **(2004)**.

[4] Martin Geidl, Gaudenz Koeppel, Patrick Favre-Perrod, et.al; Energy hubs for the future, IEEE Power & Energy Magazine, **5(1)**,.24-30 **(2007)**.

[5] Thilo Krause, Florian Kienzle, Goran Andersson; Maximizing exergy efficiency in multi-carrier energy systems, IEEE Power & Energy Society General Meeting, 1-8 **(2010)**.

[6] Matthias Schulze, Goran Gasparovic, Jieun Lee; Pricing of multi-energy network flow, IEEE International Energy Conference, 542-547 **(2010)**.

[7] Michele Arnold, Rudy R.Negenborn, Goran Andersson, et al; Model-based predictive control applied to multi-carrier energy systems, 2009 IEEE Power and Energy Society General Meeting, 1-8 **(2009)**.

[8] A.Sheikhi, A.M.Ranjbar, F.Safe, et al; CHP optimized selection methodology for an energy hub system, 10th International Conference on Environment and Electrical Engineering, 1-5 **(2011)**.

[9] M.Schulze, L.Friedrich, M.Gautschi; Modeling and optimization of renewables: applying the Energy Hub approach, IEEE International Conference on Sustainable Energy Technologies, 83-88 **(2008)**.