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# Simulation Modeling of Integrated Multi-Carrier Energy Systems

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## Abstract

Integrated multi-carrier energy systems give good possibilities to have high effectiveness of energy supply to consumers. Transformation of energy systems under the impact of internal and external factors remarkably strengthens the technological integration of those systems and supports development of integrated multi-carrier energy systems. The concept of energy hub is developed for modeling and simulation of integrated multi-carrier energy systems. Based on previous research, a simulation model of the energy hub is being developed. The basic principles of building a simulation model of an energy hub concept are discussed. Realization of simulation model using Matlab/Simulink is proposed. Simulation results for the integrated electricity and heat systems are explained to demonstrate the capabilities of the simulation energy hub model. A case study for application of the simulation model is discussed.

**Keywords:** integrated multi-carrier energy systems, simulation modeling, energy hub, energy converters, energy storage, energy consumption optimization, Matlab/Simulink software

## 1. Introduction

Modern energy supply systems, primarily electricity, heat and gas systems represent a developed energy infrastructure that provides consumers in the economic and social sectors with various energy types with the required reliability, the required quality and at an affordable price. The development and opposition of these energy systems is under the influence of a new paradigm of customer-oriented energy supply. Recently, the requirements for the reliability of power supply and the quality of the types of energy supplied to consumers have significantly increased due to computerization and digitalization of consumer production processes and the expansion in the use of “high” production technologies by the consumer.

The design and operation of these energy systems tend to consider them independently of each other. The systems under discussion however interact quite closely with each other, for example, when electricity and heat is generated using gas as fuel at cogeneration under normal and emergency conditions, when electric heaters are used by consumers in the case of accidents in the heating system, etc.

The new conditions for the development and computerization of the infrastructure energy systems contribute to the expansion of interaction between them as many new actors appear that can provide ancillary services. The consumers with controlled

load, managing their energy load, can have self-generation sources and energy storage units, and simultaneously, depending on the current conditions, be involved in conversion, storage and generation of the required type of energy; electric vehicles can deliver stored electricity to the power supply system during peak hours, etc.

The development of information and telecommunication technologies bring about additional opportunities for joint coordinated management of the expansion and operation of the energy systems under consideration.

All the above features increase significantly the interest in the research of virtually new facilities, i.e., integrated energy systems (IESs) [1, 2]. The primary basic problem here is the technology of modeling the sophisticated IESs. This chapter focuses on the main principles of the IES simulation technology relying on the capabilities of the Matlab/Simulink system and the energy hub concept.

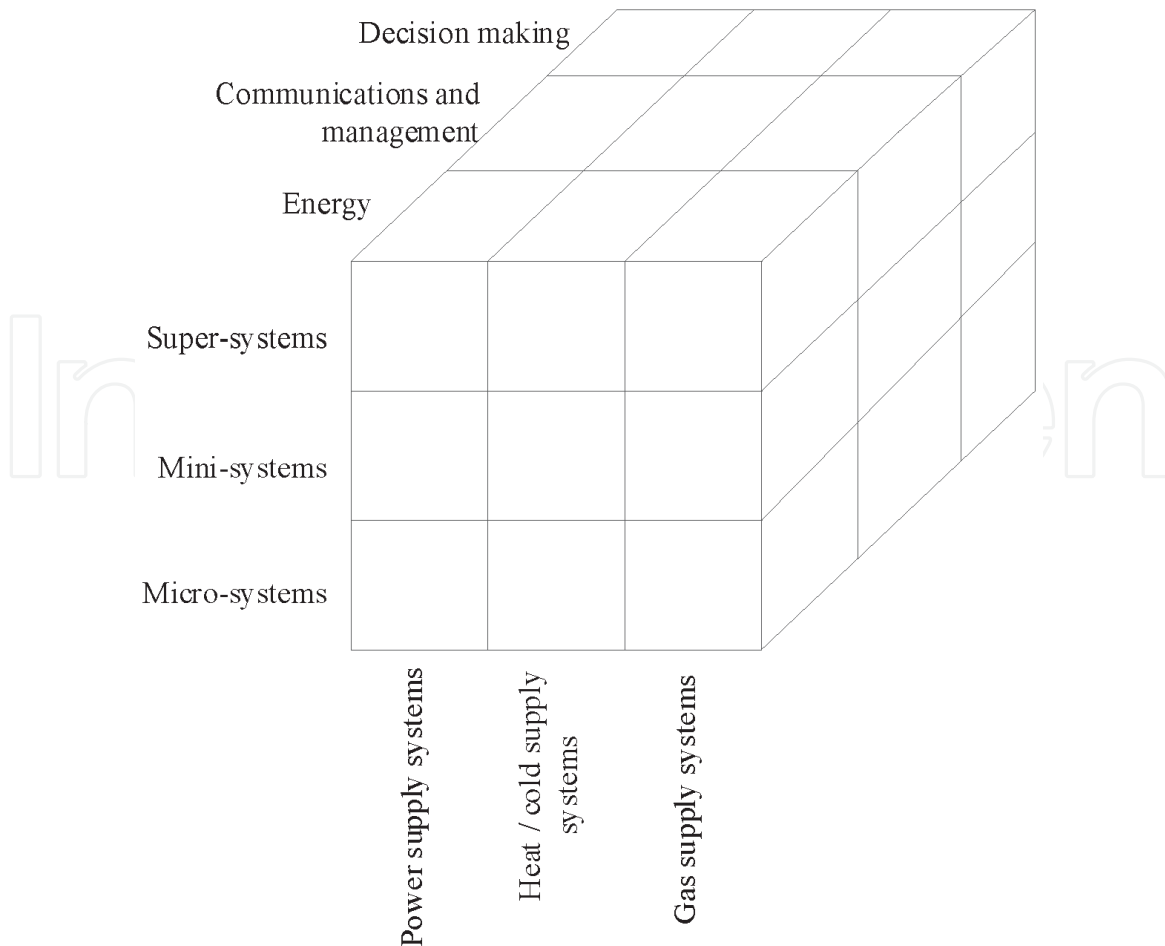
The further presentation is structured as follows. Section 2 presents basic information about the features of IES and the history of research in this strand. Section 3 provides an overview of the energy hub concept. Section 4 contains a description of the nature of mathematical models of IES based on the integration of traditional models of the components of the considered IES of power supply systems. Section 5 discusses the principles of energy hub modeling used in most of the studies conducted, and the advantages and disadvantages of the models. Section 6 analyzes the capabilities of the Matlab/Simulink system for IES modeling. Section 7 presents a new approach to building a simulation model of an energy hub developed by the authors. Section 8 discusses the proposed technology for constructing an IES simulation model. Section 9 contains a description of one of the problems solved using the developed simulation model. The conclusion to this Chapter summarizes the results of the studies performed.

## 2. Integrated multi-carrier energy systems

Objective trends in energy systems development (electric power, heat, gas, oil, oil products supply systems, etc.) lead to creation of integrated multi-carrier energy systems. These tendencies are determined by strengthening of technological integration not only during production of energy (for example, electric power and heat on the co-generation plants (CGP) by using gas as the fuel), but also under energy consumption based on implementing different kinds of energy for the same objectives. For example, it is possible to use heat from centralized heating system based on CDP or from individual electric boilers, electric or gas individual furnaces, and so on. In these cases individual energy systems (electric power, gas and heat supply systems) acquire the interdependences not only between production plants and consumption of individual systems, but also between load flows in networks of these systems. Particularly significant interrelations between individual energy systems we can meet in emergency conditions. Taking into account above mentioned peculiarities we have to consider joint operation and expansion of individual energy systems [1, 2].

In [2], the authors explain the elements of the concept of integrated energy systems as a three-layer structure in three dimensions, similar to Rubik's cube (see **Figure 1**). The groups of layers can be defined as follows:

- Layers of systems - power systems, heating/cooling systems, gas systems;
- Layers of scale - super-systems, mini-systems, micro-systems;
- Layers of functions - energy, communication and management, decision making.



**Figure 1.**  
*Three-layer structure of integrated energy systems in three dimensions.*

Integrated multi-carrier energy systems, as well as their individual energy supply systems, especially electric power, heat and gas supply systems, have important infrastructural role in the enhancement of optimal operation of different economy sectors and acceptable life of citizens in any country. There are concrete requirements to necessary level of power supply reliability to consumers and high quality of supplied energy, and also to effectiveness of operation and development of above mentioned infrastructural energy systems. It is necessary to note, that the requirements to increase reliability and quality of energy supply first of all are forming under the influence of digitalization and computerization in technological processes of consumers [3, 4].

In 1999 actually the first research project started concerning energy delivery systems from production of different kinds of energy to retail markets [5]. End use energies included electricity and heat. Such kinds of energy were studied, as electric power, gas, oil, as well as conversion between different kinds of fuel (gas power plants, hydro power plants, co-generations, heating pumps, plants for production of liquid natural gas, and so on). The possibilities of alternative storages were studied, for example hydro accumulating plants and liquid natural gas storages. This project was as the stimuli for preparation of methodology of comprehensive analysis of complicate energy delivery systems with several kinds of energy including technological, economic and ecology aspects. It was planned, that such methodology will be very flexible and will allow the integrated energy companies to make comprehensive analysis their investments and general optimization of their energy supply systems.

The project “Vision of Future Energy Networks (VFEN)” was proposed by group of authors and supported by industry [6, 7]. Horizon of planning is since 30 up to 50 years. Economic, ecology and technological aspects localize the research conditions. General hybrid approach includes different kinds of energy, which consider the synergy between electrical, chemical and heat energies (it is possible, between the other kinds of energy).

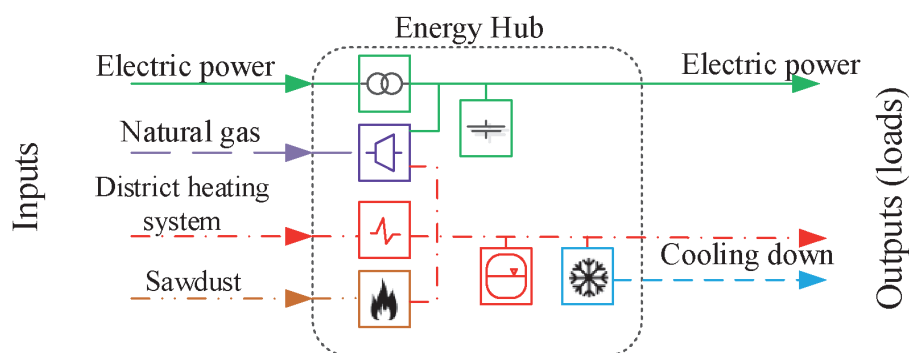
An integration of different energy systems into technologically joint body gives new functional possibility, using complex innovative technologies for integrated energy system operation and creation of smart integrated multi-carrier energy systems (SIES). Such systems have many dimensional structures of functional possibilities and development properties. They consider big number of factors: intelligence, effectiveness, reliability, controllability, flexible use of technologies for energy transformation, transportation and preservation, active demand. Protection and control systems have to react to emergency and unreal behavior and to ensure SIES after such events. It is important to develop the models and software for on-line decision making, especially in the conditions of large disturbances [8–10].

### 3. Energy hub concept

Tendency towards technological integration of energy supply systems gave birth to the notion of an energy hub [1, 8], that implies an integrated facility with multiple inputs and outputs, which represent different types of energy. This facility has internal elements for the support of some functions, i.e., transformation, conversion and storage of different kinds of energy. It is necessary to note [10], that the energy hub concept can be used rather wide – from representing some individual transmission element to a building or a part of the city.

Following [7], we will consider an example of the energy hub shown in **Figure 2**. The Figure shows the inputs and outputs of the energy hub, as well as its internal components and their interconnections (electric transformer, electric battery, micro-turbine, heat exchanger, furnace, cooler and hot water storage).

In [11], an overview of the main provisions of the energy hub concept is presented. Four main functionalities of the energy hub concept are identified, including the input, conversion, storage and output of the considered types of energy. At the same time, most of the studies discussed in the overview, use electric and gas networks as the studied facilities of the energy hub. Various types of power plants especially those based on renewable energy resources, and those relying on promising innovative technologies, such as, fuel cells, for example, were studied as sources of generation.



**Figure 2.**  
Example of a specific energy hub containing a transformer, microturbine, heat exchanger, furnace, cooler, battery, and hot water storage.



#### 4. Conventional modeling of integrated multi-carrier energy systems

It is necessary to take into account, that technological and market strengthening of individual energy systems requires more intensive studies of modeling integrated multi-carrier energy systems for the investigation and control of their operating conditions and expansion planning. There are two basically different approaches for modeling integrated multi-carrier energy systems: based on conventional mathematical models of individual energy systems [12, 13] and to use energy hub concept [14, 15].

Let us represent as the example conventional mathematical model of integrated multi-carrier energy system, including electric power and heat supply systems, in following form (1)–(6) [13]:

$$F_{obj} \rightarrow \min \quad (1)$$

subject to:

$$E_{k \min} \leq E_k^t \leq E_{k \max}, k \in N_{par}^e, t = \overline{1, T}, \quad (2)$$

$$H_{k \min} \leq H_k^t \leq H_{k \max}, k \in N_{par}^h, t = \overline{1, T}, \quad (3)$$

$$0 \leq P_i^t \leq E_{i \max}, i = \overline{1, N}, t = \overline{1, T}, \quad (4)$$

$$F_{w \max}^{it} \geq F_w^{it}, F_{q \max}^{it} \geq F_q^{it}, \quad (5)$$

and balance between electricity and heat production is:

$$\sum_{t=1}^T (W_t + Q_t) = \sum_{i=1}^N \sum_{t=1}^T (W_i^t + Q_i^t) = \sum_{t=1}^T P_i^t \Delta t, \quad (6)$$

where  $F_{obj}$  is objective function, its structure depends on the sense of solved problem for example, active power;  $F_{q_i}$  is volumes of fuel used at source  $i$  for heat production;  $F_{q_i}$  is volumes of fuel used at source  $i$  for electricity production;  $P_i$  is used (installed) capacity of source  $i$ ;  $W_i$  is supply of electricity from source  $i$ ;  $Q_i$  is supply of heat from source  $i$ ;  $W$  is electric power output total value in the system;  $Q$  is heat output total value in the system;  $E_k$  is current state parameter of electric network;  $E_{k \min}$  and  $E_{k \max}$  are technically admissible current state operating parameters limits of the electric network;  $H_k$  is current state parameter of heat network;  $H_{k \min}$  and  $H_{k \max}$  are technically admissible current state operating parameters limits of the heat network;  $P_i$  is used (installed) capacity of source  $i$ ;  $P_{i \max}$  is maximum (installed) capacity of source  $i$ .

#### 5. Main current principles of the energy hub modeling

References [14, 16, 17] present a system of algebraic equations that relate input variables of the energy hub into output variables. Both variables present different kinds of energy:

$$\begin{pmatrix} L_\alpha \\ L_\beta \\ \vdots \\ L_\gamma \end{pmatrix} = \begin{pmatrix} C_{\alpha\alpha} & C_{\beta\alpha} & \cdots & C_{\gamma\alpha} \\ C_{\alpha\beta} & C_{\beta\beta} & \cdots & C_{\gamma\beta} \\ \vdots & \vdots & \ddots & \vdots \\ C_{\alpha\gamma} & C_{\beta\gamma} & \cdots & C_{\gamma\gamma} \end{pmatrix} \begin{pmatrix} E_\alpha \\ E_\beta \\ \vdots \\ E_\gamma \end{pmatrix} \quad (7)$$

or, in matrix presentation,

$$L = C \cdot E \quad (8)$$

Energy in the input and output ports is represented by vector-columns  $E = [E_\alpha, E_\beta \dots E_\gamma]$  and  $L = [L_\alpha, L_\beta \dots L_\gamma]$ ,  $C$  is a matrix of direct relations, that describes conversion of energy forms from input to output. Each member of the matrix relates one specific input to a certain output.

In case of solving the inverse problem, a matrix of inverse conversions is introduced

$$\begin{pmatrix} E_\alpha \\ \vdots \\ E_\gamma \end{pmatrix} = \begin{pmatrix} d_{\alpha\alpha} & \dots & d_{\gamma\alpha} \\ \vdots & \ddots & \vdots \\ d_{\alpha\gamma} & \dots & d_{\gamma\gamma} \end{pmatrix} \begin{pmatrix} L_\alpha \\ \vdots \\ L_\gamma \end{pmatrix} \quad (9)$$

Relations between coefficients of inverse and direct transformations have a unique form:

$$d_{\beta\alpha} = \begin{cases} c_{\alpha\beta}^{-1} & \text{if } c_{\alpha\beta} \neq 0 \\ 0 & \text{else} \end{cases} \quad (10)$$

Should there be  $N$  output ports and one input port, the energy through each output channel would be distributed following the equation:

$$E_{im} = \sum_{n=1}^N d_{im} L_{in} \quad (11)$$

It is necessary to note, that the most part of references, which deal with the energy hub modeling, including dissertations [18, 19] for different problems investigations concerning integrated multi-carrier energy systems, are using linear energy hub models. These studied problems include calculation and optimization of power flow in integrated multi-carrier energy systems, reliability of electric power and heat supply to consumers, optimization of integrated energy system expansion, and some others [1, 10, 12, 14–17].

Above mentioned studies showed potentials of considered approach to use the linear energy hub model and at the same time the problems of its application. The matter is, that it is necessary to determine the matrix coefficients in (7), which relate inputs and outputs of the energy hub. But this determination faces some difficulties even for linear case. Really these coefficients can have complicate structure including non-linearities. Moreover, above mentioned energy hub models allow to solve only stationary problems in integrated multi-carrier energy systems. Dynamic problems consideration based on energy hub concept had not been studied yet, what had noted as the favorite direction of further investigations [18].

It is necessary to draw the attention on the first known results of dynamic problems study in [20] using conventional mathematical model of integrated energy system based on technique of the theory of singular perturbations (small parameters). This technique was used for presentation of individual energy systems in the integrated multi-carrier energy system.

The above mentioned peculiarities of energy hub modeling stimulate to search the other possibilities to solve these problems. Next Section allows such possibilities.

## 6. Matlab/Simulink capabilities and simulation model construction

The simulation modeling approach can be as the basic technology for construction of integrated multi-carrier energy system model. Let us use the capabilities of Matlab/Simulink software for suggested technology development. The following components of necessary simulation model construction procedure of integrated multi-carrier energy systems we will have to take into account:

- The initial information about modeled integrated energy system includes the topology and parameters of different kinds of elements (objects) of individual energy systems. We have to note the initial element in every individual energy system, which will be the start point for topological model creation of every individual energy system.
- Current versions of Matlab/Simulink software include rather developed library of models for elements of different technological systems – electric power, pneumatic, hydraulic ones, and the others. These models of elements are presented using transfer functions and can be implemented for dynamic processes study in different technological systems. We deal with steady state conditions, therefore it is necessary to convert initial dynamic models into the static form.
- The above mentioned library of Matlab/Simulink software does not contain complicated elements with multi-input and multi-output structure. Such elements are energy hubs. The co-generation plant can be as the example of such complicated element (object) with one input (gas) and two outputs (electric power and heat). At the level of consumption such elements of integrated multi-carrier energy system include conversion function of one kind of energy into the other. The energy hub models are forming the specific additional library. These models also implement such functions as energy storages and summation of different kinds of energy.
- It is necessary to note, that there are two kinds of energy conversion elements: 1) they change the characteristics of the energy channel without conversion of energy form into the other one (for example, electrical transformer, heat exchanger, and so on); 2) they change not only characteristics of the energy channel, but also convert one kind of energy into the other one.
- Different kinds of energy in integrated multi-carrier energy system have different measurement units (kWh, Gcal, etc.). Therefore Joule (J, W.s) is considered as a basic unit of measurement. The transformation function of different unit to the basic one was implemented using Matlab/Simulink software.
- After the creation of topological models of different individual energy systems networks using above mentioned procedures it is necessary to connect them each other. Energy hub models of energy production plants (co-generation plants, heating plants, etc.) and complex consumers with several kinds of consumed energy (electric power, heat, etc.) play the role of such connectors.
- Constructed simulation model of integrated multi-carrier energy system really is the basic part of any full simulation model for solving some concrete



problem of integrated energy system. The statement of concrete solved problem requires additional procedures for problem formalization and results interpretation. For example, the solving loss minimization problem in electrical network requires load flow calculation as the basic procedure and optimization algorithm formalization for solving full necessary problem.

After above mentioned procedures the simulation model of integrated multi-carrier energy system is ready to usage for solving different problems.

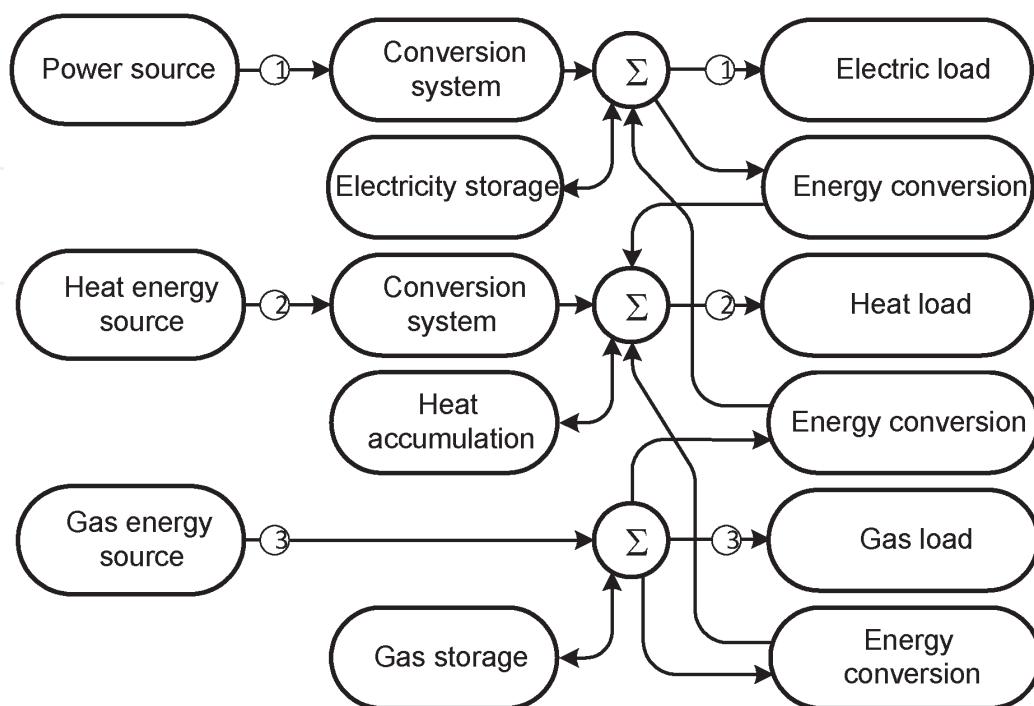
## 7. Elements of technology for modeling of the energy hub

**Figure 3** shows general structure of the energy hub simulation model, which was constructed by Matlab/Simulink software capabilities [21]. This structural scheme presents three energy supply channels: 1 - electric power; 2 - heat; 3 - gas. The model implements the functions of transformation, conversion and storage of energy, and an additional summation function whose concept is understandable from **Figure 3**.

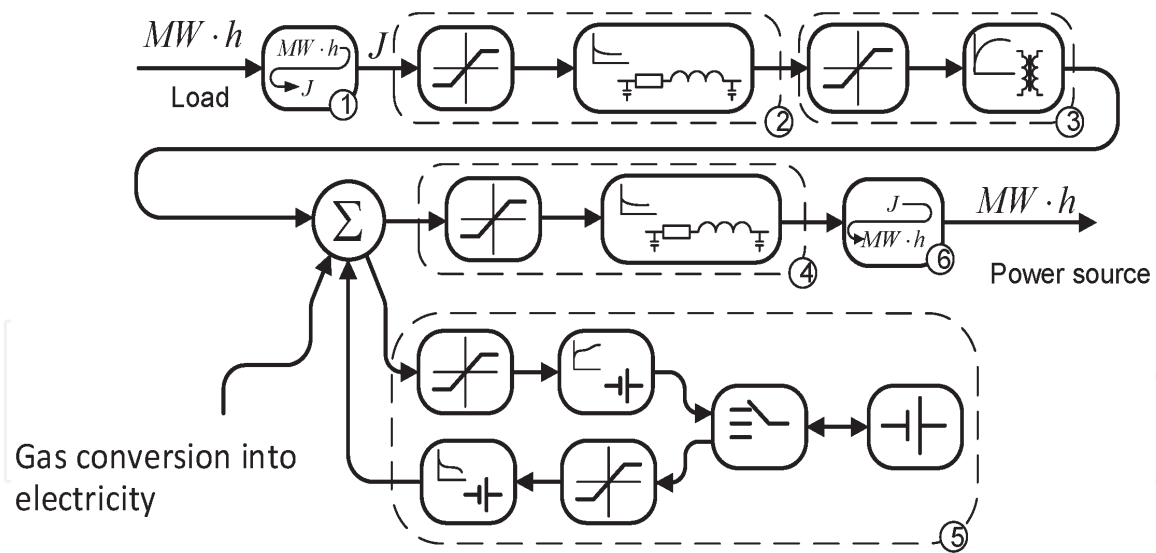
**Figure 4** presents detail structure of the energy hub simulation model for the electric power supply channel using representation of elements by images of Matlab/Simulink software. Here 1 and 6 present direct and inverse transformations of state variables; 2 and 4 present the electricity transfer; 3 presents the transformer sub-station model; 5 presents the energy storage device model.

**Figure 4** takes into account the peculiarities of simulation modeling procedures of Matlab/Simulink software, including propagation and conversion of presented system.

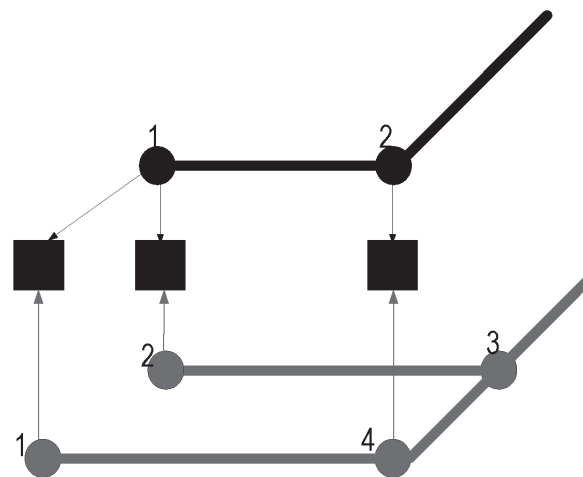
**Figure 5** gives an example of an integrated scheme based on two energy supply channels. A black line here denotes a channel of a heat network; gray one denotes a



**Figure 3.** General structure of the energy hub simulation model. (channels: 1 - electric power supply; 2 - heat supply; 3 - gas supply).



**Figure 4.**  
 Flow chart of electric power supply channel for the energy hub simulation model.



**Figure 5.**  
 An integrated scheme based on two energy supply channels.

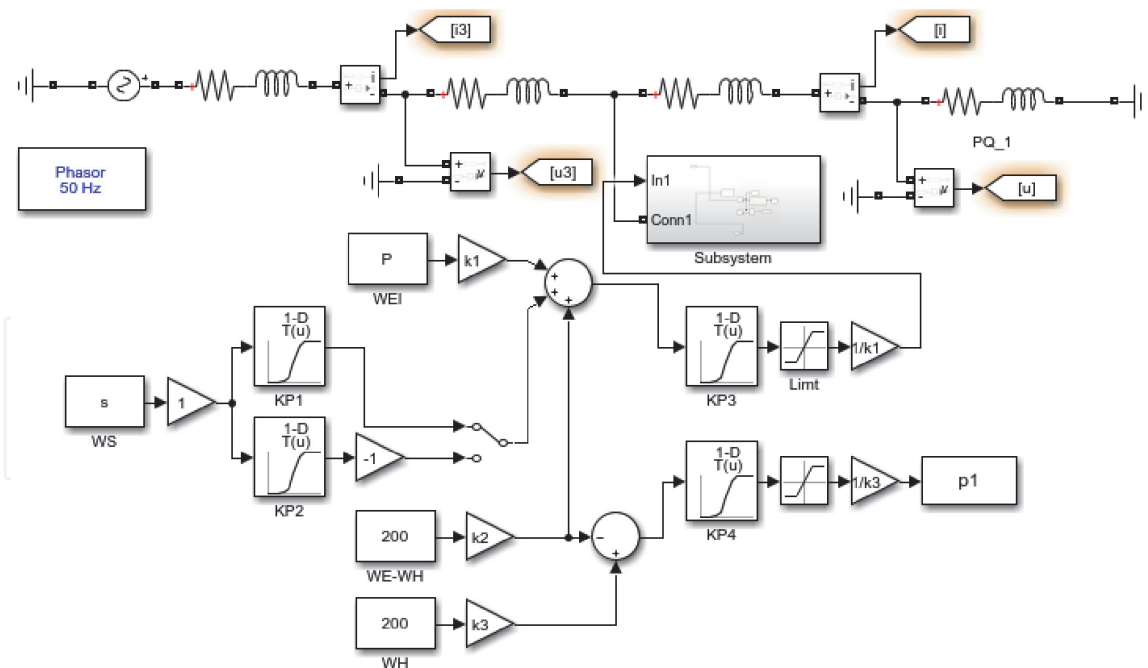
channel of an electric network. A squares denote hubs locations, which represent electricity and heat consumers.

The example in **Figure 5** shows, that two energy channels (electric power and heat) go to one consumer. Taking into account storage systems and systems for conversion of electric power into heat we will have complex energy hub based on presented consumer.

Rather simple elements of electric power and heat supply systems can be presented by simulation models from Matlab/Simulink library. According to above noted approach, it is necessary to create additionally the library of energy hubs simulation models. **Figure 6** presents the integrated simulation model of energy supply systems (electric power and heat) including energy hub with two energy supply channels.

The simple elements of individual energy supply systems are used from the basic library of Sim Power Systems which is sub-system of Matlab/Simulink.

WEI and WS elements represent energy consumption and storage, which connected by electric power supply channel. WH is the energy consumption by heat supply channel. KP1 - KP4 are the elements, which works taking into account efficiency of the energy conversion. WE-WH represent electricity converted into the heat energy.



**Figure 6.**  
Construction of integrated simulation model with two energy supply channels in Matlab/Simulink.

## 8. An algorithm of simulation model construction for integrated multi-carrier energy systems

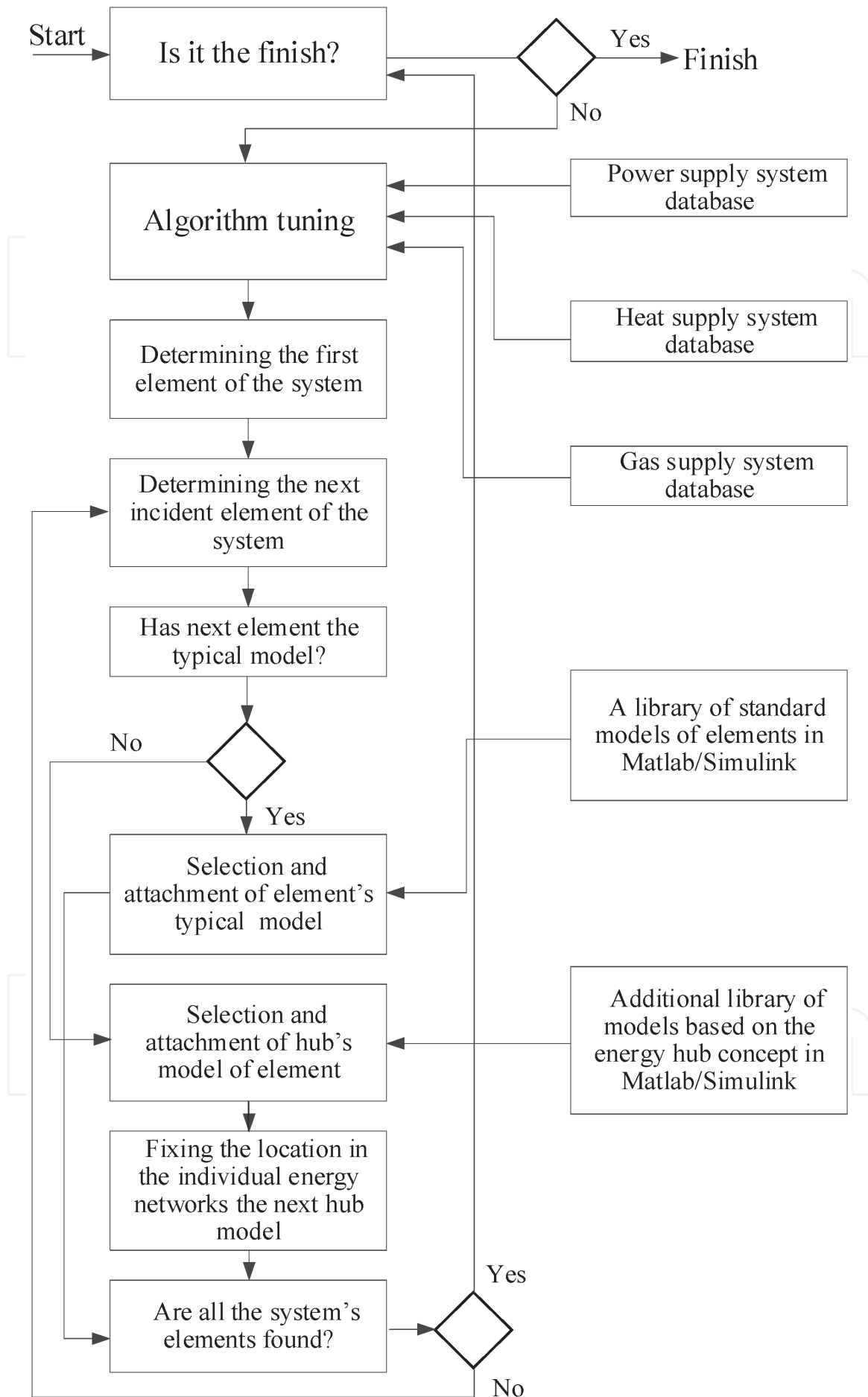
A general approach to constructing a simulation model of an integrated multi-carrier energy system and to solution of different problems with its help can be represented as follows [21, 22] (see **Figure 7**).

Input data about the studied integrated multi-carrier energy system is prepared including the matrices of parameters of individual energy systems (their network topologies, electric and hydraulic resistances of electric lines and pipelines), as well as vectors of nodes parameters (electric power and heat generations, loads, storages, etc.).

The necessity to use of two libraries of integrated energy system elements was noted earlier in Section 6. An algorithm for simulation model construction of integrated multi-carrier energy system selects required model of the next element from the point of view of individual energy system topology (depending on the element type) either from library of typical elements in Matlab/Simulink software or from additional library, which includes the energy hubs models. After that required model attaches to necessary node (nodes for energy hub model) of integrated energy system. As it is noted in Section 6, the energy hub model has several inputs and several outputs, which connect different individual energy systems into integrated multi-carrier energy system.

As we said in Section 6, above mentioned procedure creates so called basic part of integrated energy system simulation model. It is necessary to work out an additional part for simulation model, which represents the specifics of concrete calculated problem (see Section 6).

Matlab/Simulink software contains the object-oriented programming language, which has used for construction of integrated multi-carrier energy system simulation model. **Figure 7** represents simplified flow chart of the basic part of discussed algorithm taking into account three individual energy systems: electric power, heat and gas supply systems.



**Figure 7.** Flow chart of algorithm for constructing basic part of integrated energy system simulation model.

## 9. Illustrative case study

An integrated energy system is considered including the electricity and heat supply systems of a block of 9 dormitories of a University campus. The diagram of the electric network of the integrated energy system is shown in **Figure 8**, the diagram of the heat network is topologically about similar, since each dormitory is a consumer of both electricity and heat. The diagram of the heat network is not given, since the load of heat pipelines in the problem solved does not including, but, on the contrary, decreases, i.e., there are no network constraints on heat transfer.

In **Figure 8** FS is feeding substation, the nodes 11, 12, 13, 14, 15 are transformer substations 6/0.4 kV.

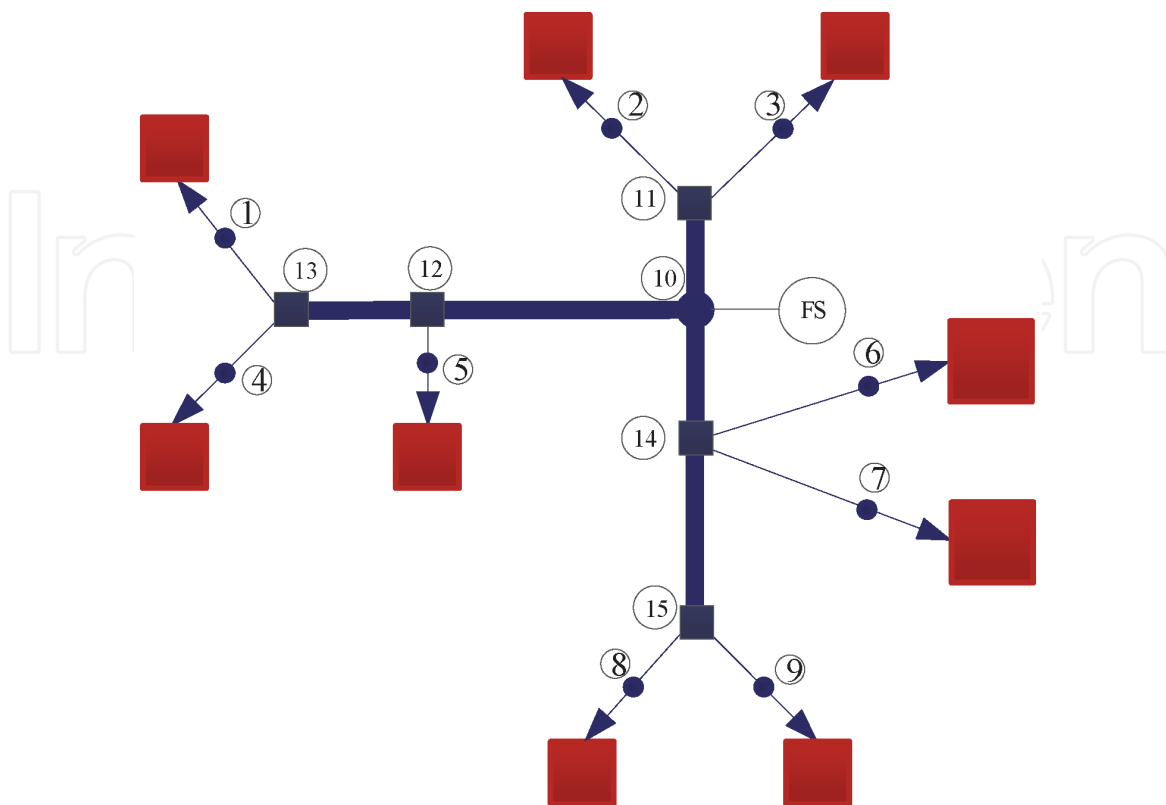
**Figures 9 and 10** indicate the total annual electricity and heat consumption curves for the entire block of dormitories, respectively. We assume that thermal energy is consumed only for heating. The daily heat load curve is uniform. The irregularity factor of daily electrical load curve is 0.4 (the ratio of the load value during the night minimum period from 23:00 to 7:00 to the peak load value). Daily curves of heat and electrical load are the same for all dormitories.

We consider the conditions for preventing overload of the electrical network. To this end, the total load power during the night minimum of the daily load curve, including its power level plus the amount of power consumed to convert electricity into heat, should not exceed the daily maximum load. In this case, the load flow in the electrical network will not change and there will be no overloads.

**Table 1** shows monthly data on the parameters of electricity supply to consumers on the University campus.

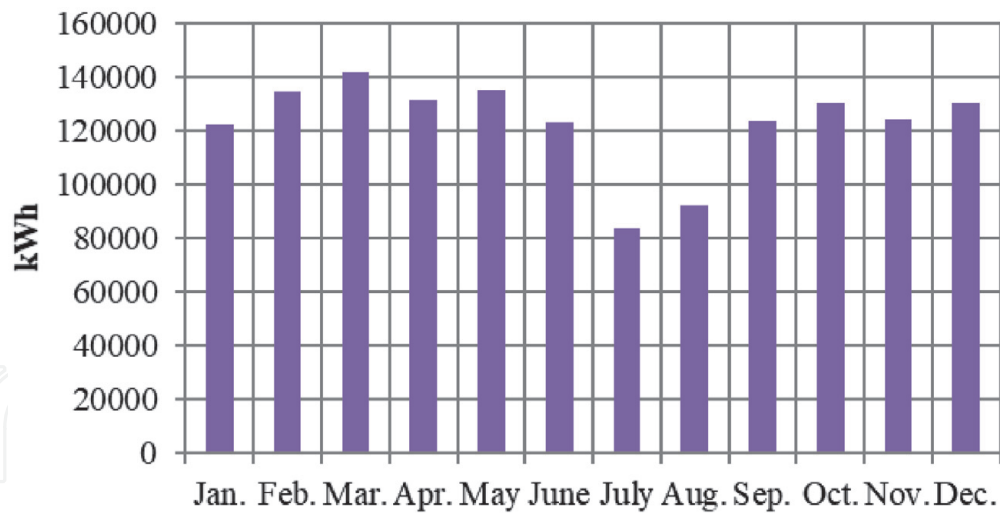
The values of daily maximum load are used to calculate the values of conventional maximum possible electricity consumption of the campus per month with the formula:

$$E_{\text{mon. max}} = (P_{\text{day. max}} \cdot 24) \cdot 30, \quad (12)$$

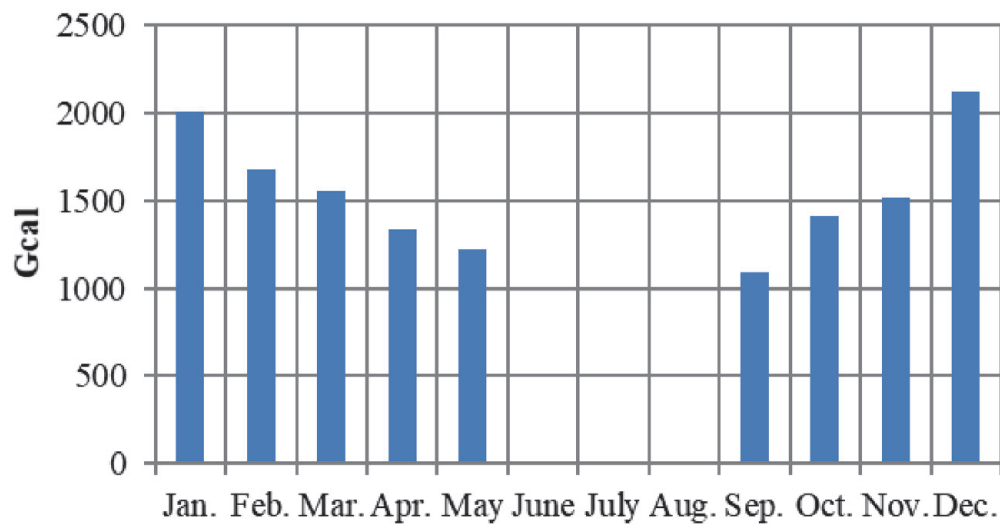


**Figure 8.**  
Diagram of the electrical supply system.





**Figure 9.**  
 Electricity consumption of 9 dormitories.



**Figure 10.**  
 Heat consumption of 9 dormitories.

where  $E_{mon. max}$  is the maximum possible conventional value of electricity consumption per month;  $P_{day. max}$  is a daily maximum load.

The amount of electricity that can be converted into heat (conversion potential) is determined by:

$$E_p = E_{mon. max} \cdot 0,6 \cdot 0,33, \quad (13)$$

where  $E_p$  is the potential for converting electricity into heat per month; coefficient 0.6 reflects the share of free power within the night minimum load; coefficient 0.33 determines the share of duration of the night minimum daily load curve (8 hours), during which electricity is paid for at the minimum night rate.

Conversion of electricity into heat is carried out according to the relationship:

$$1 \text{ kWh} = 0,00086 \text{ Gcal.}$$

In **Table 1**, the last two columns indicate two options for the amount of electricity to be converted to heat: the entire (100%) conversion potential and 50% of this potential.

	Power consumption of 9 dormitories, kWh	Night zone (from 23 to 7), kWh	Payment for electricity consumption at night without conversion, \$	Daily peak load, kW	Maximum electricity consumption per month, kWh	The amount of electricity (potential) to convert to heat per month, kWh	50% of electricity for conversion to heat per month, kWh
Jan.	122000	47000	519	476	343000	67900	34000
Feb.	134000	50000	547	459	331000	65500	33000
Mar.	142000	53000	583	418	301000	59600	30000
Apr.	131000	48000	526	392	282000	55900	28000
May	135000	50000	552	489	352000	69700	35000
June	123000	48000	525	441	318000	62900	31000
July	83600	33000	361	324	233000	46200	23000
Aug.	92300	36000	401	344	248000	49100	25000
Sep.	123600	48000	533	443	319000	63100	32000
Oct.	130000	51000	561	410	295000	58500	29000
Nov.	125000	49000	536	450	324000	64200	32000
Dec.	130000	51000	559	489	352000	69700	35000

**Table 1.**  
University campus power consumption data.

Following the current pricing system for electricity and heat, electricity rates are differentiated throughout the day: a preferential night rate from 23:00 to 7:00 is \$ 0.011 per kWh. Heat rate is \$ 20.6 per Gkal.

In general terms, the following relations are valid:

$$C_e = E_p \cdot t_3, \quad (14)$$

$C_e$  is the cost of electricity before conversion into heat.

$$C_{tn} = E_t \cdot t, \quad (15)$$

$t$  is heat tariff;  $E_t$  is thermal energy.

The following relations are valid:

$$C_e = C_{en} + C_{ed}, \quad (16)$$

$$C'_e = C_{en} + C'_{en} + C_{ed}, \quad (17)$$

$$C_t = C_{tn} + C_{td}, \quad (18)$$

$$C'_t = C_{tn} - C'_{tn} + C_{td}, \quad (19)$$

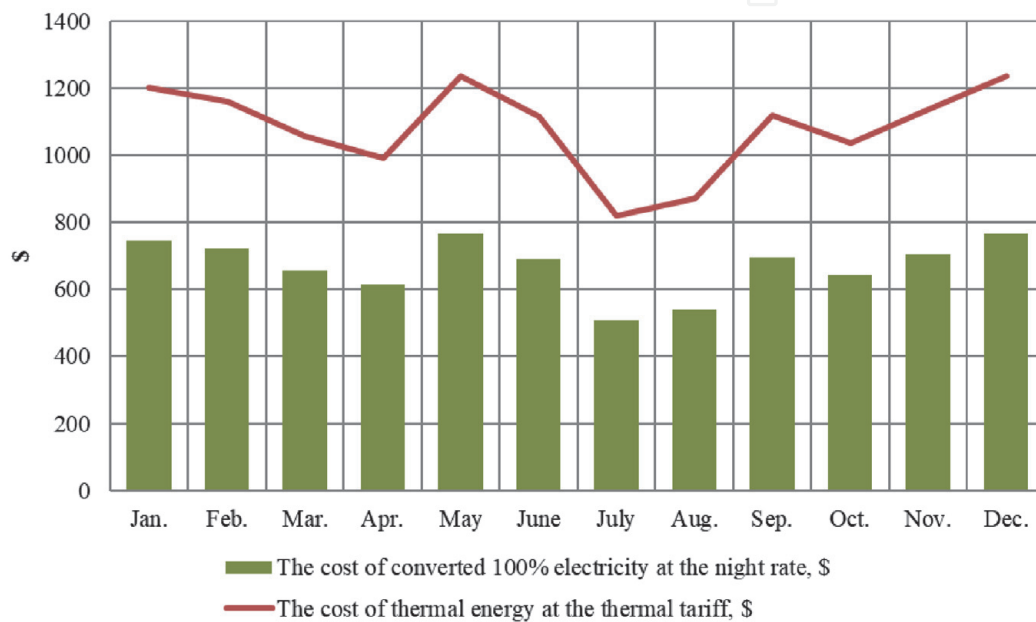
$$C'_{en} < C'_{tn}, \quad (20)$$

where  $C_{en}$  is cost of electricity before conversion at night;  $C_{ed}$  is cost of electricity before conversion to daytime;  $C_t$  is cost of thermal energy before conversion;  $C_{tn}$  is the cost of thermal energy at night;  $C_{td}$  is the cost of thermal energy in the daytime;  $C'_e$  is cost of electricity after conversion;  $C'_{en}$  is cost of electricity at night after conversion;  $C'_t$  is cost of thermal energy after conversion;  $C'_{tn}$  is the cost of thermal energy after conversion at night.

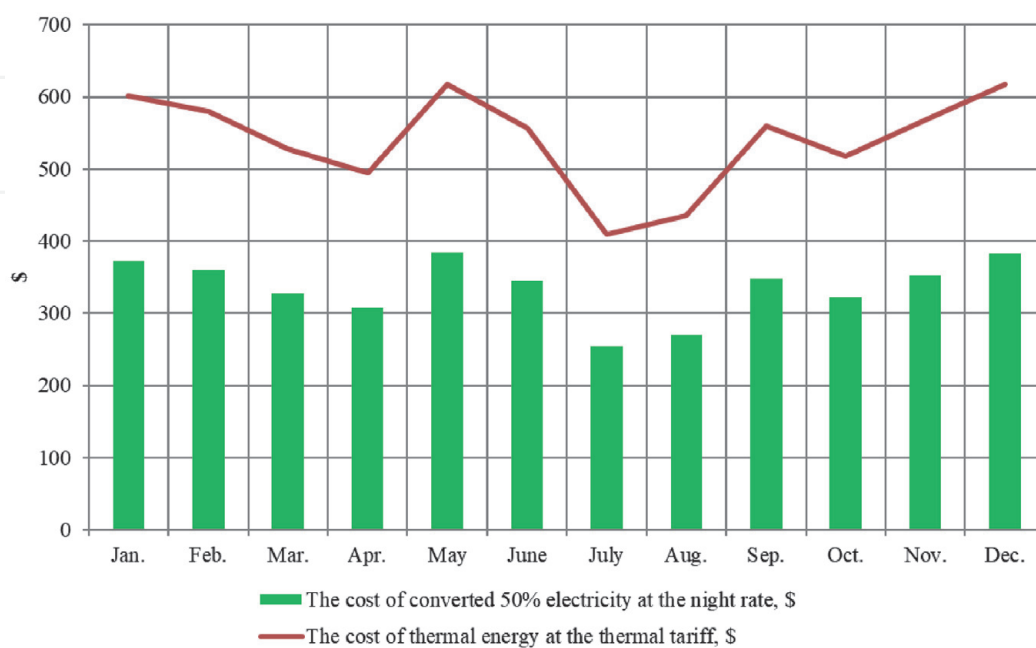
The results of the calculations of the considered options are presented in **Figures 11** and **12**.

Let us return to the condition of preventing the electrical network overloads, formulated above. An analysis of the transfer capability and loading of individual ties lines in the case of electricity conversion into heat, according to the condition assumed, shows that this loading is not the same (see **Table 2**).

It is important to estimate some limiting volume of conversion of electricity into heat at night taking into account the possibilities of electrical network. These possibilities depend on free transfer capabilities of ties and permissible loading of transformers on feeding substation. Required parameters of electrical network and basic load flow calculation without consideration of active losses you can see on the **Table 2**. Consumption load at night which found on the previous stage (basic load flow) for each consumer is 490 kW. The permissible loading of transformers on



**Figure 11.**  
 Comparison of payment with electricity conversion into heat factored in 100%.



**Figure 12.**  
 Comparison of payment with electricity conversion into heat factored in 50%.

Ties numbers	10–11	10–12	10–14	12–13	14–15
Transfer capabilities of ties, kW	2100	2100	2100	2100	2100
Load flow, kW	980	1470	1960	980	980

**Table 2.**

Required parameters of electrical network and basic load flow.

feeding substation is 6000 kW. Let us consider, that cable lines from transformer substations 6/0.4 kV to import of electricity into building do not have the limits of transfer capabilities. As for limiting volume of heat supply for each consumer, let us to consider 380 kW after re-calculation into converted electricity.

Let us formalize optimization problem as following:

Objective function:

$$\Delta P_{FS} \rightarrow \max, \quad (21)$$

Subject to:

$$\Delta P_{FS} \leq \Delta P_{FS \text{lim}}, \quad (22)$$

$$P_{ij} \leq P_{ij \text{lim}}, \quad (23)$$

$$P_{kheat} \leq P_{kheat \text{lim}}, \quad (24)$$

$$\Delta P_{FS}^{l+1} = \Delta P_{FS}^l + h \frac{\Delta P_{FS}^l}{1/\Delta P_{ij}}, \quad (25)$$

$$\Delta P_{ij} = P_{ij \text{lim}} - P_{ij}, \quad (26)$$

where  $\Delta P_{FS}$  is additional power for conversion into heat;  $P_{ij \text{lim}}$  is transfer capability of tie  $ij$ ,  $i, j = 1, 2, 3$ ;  $P_{kheat \text{lim}}$  is top re-calculated to electricity level of heat for consumer.

$k, k = 1-9$ ;  $h$  is the step of optimization;  $l$  is the number of iteration. The second member in right part of (25) is the similar to gradient of objective function.

Several beginning steps of optimization are along the ray 10–11 to use the possibility for additional conversion of electricity into heat. The results of these iterations are 380 kW for consumer 2 and 380 kW for consumer 3 as the additional converted volumes of electricity. These volumes along the ray 10–11 are top volumes for additional conversion. One next iteration deals with the ray 10–12, where it is possible to use 380 kW for consumer 5 and the rest on this ray 250 kW ( $2100 - 1470 - 380 = 250$ ) for consumers 1 or 4. The iteration along the ray 10–14 allows to use 140 kW additional converted electricity ( $2100 - 1960 = 140$ ) for consumers 6 or 7 or 8 or 9.

It is possible to see, that we could use more electricity for additional conversion into heat, but the problem is in the electrical network limitation.

## 10. Conclusion

Creation of the integrated multi-carrier energy systems is progressive trend in development of energy supply systems. Joint expansion of individual energy systems leads to enhancement of economic efficiency and reliability of energy supply to consumers. It is necessary to have the efficient tools for expansion planning and operation management and control of integrated multi-carrier energy systems.

Energy hub concept is progressive way for modeling and simulation of integrated energy systems, but there are some problems in determination of the coefficients of connection of each individual input and each individual output of the energy hub simulation model.

This Chapter represents new approach to solve above mentioned problems based on the possibilities of Matlab/Simulink software taking into account the elements of energy hub concept. The main idea of suggested approach deals with the construction of simulation model of integrated multi-carrier energy system considering the models of simple typical elements from the Matlab/Simulink library and complicate energy hub models from additional library, which is created based on Matlab/Simulink software possibilities.

Illustrative case study shows the efficiency of suggested approach.

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