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Adequacy modeling and evaluation of multi-carrier energy systems to supply energy services from different infrastructures

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ABSTRACT

Development of MCESs (Multi-Carrier Energy Systems) can make the energy supply more reliable and efficient. Due to the redundancy potential of these systems, in case of an energy carrier interruption, consumers may be able to supply part of their loads from other energy infrastructures. This paper presents an approach for evaluating the adequacy of MCESs considering the dependencies of energy carriers at both generation side and demand side. To model the adequacy of generation systems supplying different forms of energy, a new methodology is presented, which considers the limitation of primary resources and takes into account the COPTs (Capacity Outage Probability Tables) of different energy infrastructure components. The model incorporates the impact of load dependencies at the demand side. A new focus is set up, by considering the outputs as *services* that can be provided through different types of energy supply. Illustrative results are presented to show the application of the proposed models to multi-energy systems.

1. Introduction

1.1. Motivation

The adequacy of different energy infrastructures is often analyzed independently in planning studies [1–3]. However, in a MCES (Multi-Carrier Energy System) from the primary resources to the end-users, energy carriers can be converted into each other. Fig. 1 shows a MCES in which converters and appliances are used to provide different services from different energy infrastructures. In such a multi-carrier environment, there are some primary resources (e.g., natural gas) that are consumed by several energy infrastructures in order to supply different energy carriers demand (e.g., gas, heat and electricity) [4]. Since failure or high demand of one energy infrastructure can result in shortage of these primary resources, it is necessary to consider resource sharing in adequacy analysis of energy systems.

The focus in this paper is set on the energy-based *services* than can be provided through different types of energy supply systems or infrastructures. The possibility of providing a given service from different energy sources is represented by introducing links among energy converters and appliances. The focus on the services is a novel view with respect to the traditional way to describe the outputs as given energy values. From the energy services point of view, the energy used to provide the same service (e.g., maintaining the temperature constant in an ambient, or cooking a given type of food) can be different if different energy sources are deployed.

The energy converters link the inputs from various energy sources to the corresponding outputs. As the energy converters can establish redundant connections between inputs and outputs, reliability of supply can be increased from the consumers' perspective, because supplying the services are no longer fully dependent on a single energy source or network [5]. However, from the upstream energy system perspective, an outage of one energy carrier forces the consumers to replace their demand with another, which may propagate the energy curtailment to other networks. For example, in case of gas curtailment, the consumers will demand more electricity for using electric heaters instead of gas heaters, which may make the electrical power system to be at risk. Therefore, loads dependency should also be considered in adequacy analysis studies.

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Nomenclature

Acronyms

CHP	Combined heat and power
COPT	Capacity outage probability table
DS	Demand side
DSA	Demand side appliance
DSEC	Demand side energy converter
EA	Extra appliance
EENS	Expected energy not supplied
FOR	Forced outage rate
GSEC	Generation side energy converter
HLI	Hierarchical level I
LDC	Load Duration Curve
LOLP	Loss of load probability
MCES	Multi-carrier energy system
MCEH	Multi-carrier energy hub

Subscripts and superscripts

α, β, ω	indices for energy carriers
ξ	index to show the type of consumer
ϕ	index to show the order of conventional energy converter/resources block
b	index to show the order of renewable energy type
h	index for MCEH
j	index to show the order of energy resources
k	index to show the order of services
m, n, γ, δ	indices to show the order of energy carriers
r	index for renewable energy sources
w	index to show the order of renewable energy model states
y	index to show the order of the constitutive units of energy converters or resources
z	index to show the order of system states
A	index for appliances
C	index for energy converters
DS	index for demand side
E	index to show extra appliances
GS	index for generation side

Parameters and variables

η	efficiency of an energy converter or appliance
ε	utilization factor of extra appliances
ζ	output capacity of energy converters or resources
λ	failure rate
μ	repair rate
ρ	binary parameter
π	interruption cost of one energy carrier
Φ	number of conventional blocks (energy converters or resources)
Π	total interruption cost
Ξ	number of the types of consumers
Δl	amount of energy shortage
$\bar{e}$	maximum available power to supply the loads
p	probability of state
q	a parameter between 0 and 1
B	number of renewable resource types
H	number of MCEHs
J	number of primary energy resources
K	number of services
M, N	number of energy carriers
Q	probability of failure
R	probability of success
V_{ξ}	number of consumers with type ξ
W	number of renewable energy model states
$X$and $\dot{X}$	dispatch factor that represents the portion of one input in supplying one output
Y	number of units constituting a block of energy converters or resources
Z	number of system states

Vectors and matrices

$\mathbf{e}$	demand vector that should be supplied by energy converters at generation side
$\mathbf{g}$	services demand vector
A	appliances matrix describes the mapping of the service demands to the appliances inputs
C	energy converter matrix mapping the powers from the output to the input
L	demand vector that should be supplied by energy converters at the demand side
X	dispatch matrix that represents the portion of each input in supplying the outputs

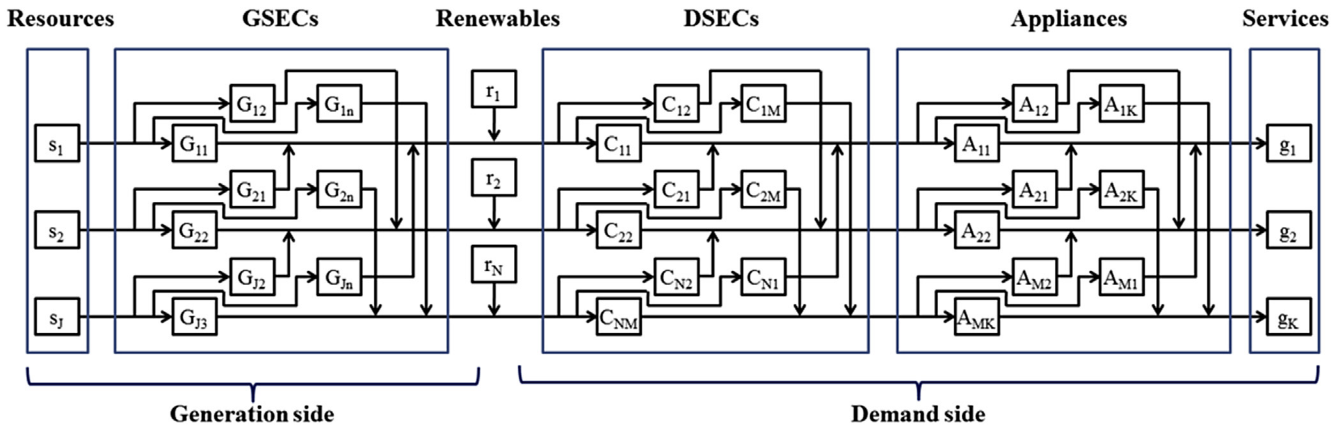

Fig. 1. MCES model for HLI adequacy analysis.

1.2. Literature review

Reliability evaluation of the electric power system has been studied in different researches. In Ref. [1] the power system reliability problem is evaluated in three Hierarchical Levels: reliability of the generation system (HLI), reliability of the composite generation and transmission system (HLII), and reliability of the complete system (HLIII). Moreover, the analysis of the power system reliability considering the reliability of gas supply has been addressed in several researches [6–9]. In Ref. [6] the NERC (North American Electric Reliability Corporation) highlights the impact of natural gas delivery on reliability of the electric power system and considers unexpected fuel transportation contingencies in power systems adequacy. The risks associated with the security of the natural gas network with gas-fired generation units are addressed in Refs. [7–9] and security-constrained unit commitment is presented to consider the short-time impact of natural gas prices on generation units scheduling.

One the other hand, the development of energy converter technologies (e.g., CHP (Combined Heat and Power), fuel cells) has increased the inter-dependency between different forms of energy [10,11]. This issue has attracted the attention of researchers to investigate on the characteristics of multi-carrier energy systems [12–14]. Reference [12] presents a coupling matrix to model the relation between the energy at the inputs and the loads in a MCEH (Multi-Carrier Energy Hub). In Ref. [15] the previous presented model of MCEHs is extended to consider the stochastic behavior of customers and model the implementation of demand response programs. Reference [16] presents a comprehensive linearized model for optimal design of a MCEH. Reference [17] analyzes distributed multi-generation systems in MCESs and discusses the benefits of these systems. The method for combined optimization of energy systems presented in Ref. [18] includes multiple energy carriers and conversion between different energy infrastructures. Reference [19] decomposes the problem of multi-carrier OPF (Optimal Power Flow) into its traditional separate OPF problem to develop a general modeling framework for coupled power flow studies.

In addition to the financial benefits of MCESs, for the purpose of enhancing the operational efficiency of the energy systems a key benefit of MCESs can be identified in the area of reliability of supply. A model for reliability evaluation of a MCEH is presented in Ref. [5], considering the power inputs to be always available. A reliability evaluation analysis of MCEHs is presented in Ref. [20] considering the dynamic behavior of thermal loads. Reference [21] developed a model predictive control strategy to mitigate the effects of cascades in transmission lines and gas pipeline networks; to minimize load-shedding after a disturbance, line outages are incorporated into the economic dispatch formulation.

1.3. Paper contributions

In previous studies, the electric power system adequacy has been evaluated based on capacity availability of power plants, without considering the limitation of the primary resources of energy. The study presented in this paper considers the details of supply side and energy services. The scope of the classical HLI analysis is extended to incorporate the multi-energy dependencies of the services and the limitations on primary resource availability.

The specific contributions of this paper are:

1) modeling the adequacy of MCESs including both the generation side and the demand side, taking into account that some energy services can be provided through different types of energy supply;
2) developing a model that considers the mutual dependency of multi-carrier energy demand in adequacy analysis, considering that availability of alternative supply to a service creates load-side dependency;
3) incorporating the limitation of primary energy resources in the formulation of the adequacy analysis problem.

In order to assign the primary energy resources to different energy infrastructures and calculate the energy not supplied in each infrastructure, the problem is formulated in a linear manner that can be implemented in multiple system states and for multiple time periods. Similarly to other HLI studies, the energy distribution networks are assumed to be always available.

1.4. Paper organization

The rest of the paper is organized as follows: Section 2 addresses system modeling and problem formulation. Section 3 discusses the adequacy evaluation procedure. Section 4 presents the numerical study application. Section 5 contains the conclusions.

2. System components modeling and problem formulation

2.1. Modeling the multi-carrier demand in normal conditions

To consider the dependency of different forms of energy in the demand side, this section introduces a model that extends the models presented in literature. As shown in Fig. 2, the general form of a consuming MCEH has multiple ports, including several inputs (e.g., electricity, natural gas and district heat) to supply different loads (e.g., electricity and heating) at output ports [12,13]. Between the ports, different energy carriers are converted into each other using energy converters to supply loads more efficiently and with a higher degree of reliability.

To minimize the costs of the system in optimization problems, a coupling matrix has been defined in previous studies, relating the loads to the energy inputs [12,13]. However, the model does not consider the impact of both energy converters and appliances. In response, in this paper, a two-stage model is considered to reach different services or goods (e.g., cooking, lighting) through the inputs of MCEH. The first stage can include a direct link (e.g., gas to gas) or a converting component (e.g., gas-fired micro-turbine for converting gas to electricity). For simplicity, all components of this stage are called *energy converters*. The second stage includes the *appliances* (e.g., electric cookers) that consume a form of energy to supply some services. This two-stage model lets us to consider the

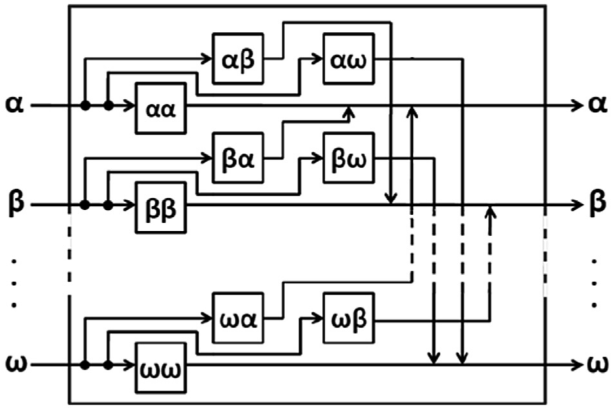

Fig. 2. General model of MCEH presented in the literature [12,13].

impact of extra appliances usage in the modeling. It is also possible to consider services demand profiles in the presented model. Every type of building and consuming energy hub (e.g., hospital, hotel, and manufactory) with any size can be considered in this model.

The service demand of MCEH h is represented by using a vector $\mathbf{g}^h$. The kth entry in vector $\mathbf{g}^h$ represents the energy amount that is reached through the corresponding appliances to satisfy the supply of service k. The matrix $\mathbf{A}^h$ is defined to represent the role of the appliances. Each entry A_{mk}^h of matrix $\mathbf{A}^h$ includes two terms: X_{mk}^{hA} that represents the portion of appliance m in supplying service k, and the efficiency η_{mk}^{hA} of that appliance. For a small building, the entries X_{mk}^{hA} are often 0 or 1. For example, the corresponding entry for the appliances that converts electricity to lighting is usually 1 and for the appliances that convert gas to lighting is 0. The first stage (energy converters) is modeled by a matrix $\mathbf{C}^h$. Each entry C_{nm}^h of this matrix includes two terms: X_{nm}^{hC} representing the portion of each load m that is supplied by the energy infrastructure n through an energy converter, and the efficiency η_{nm}^{hC} of that energy converter. If the efficiency of the components were equal to unity, the summation of each column of $\mathbf{A}^h$ and $\mathbf{C}^h$ would be a unity vector. If the number of services is K, the number of energy carriers for supplying appliances is M, and the number of energy infrastructures is N, then, the general model of a MCEH as expressed in the following equations can be used to calculate the demand of different energy carriers:

$$\underbrace{\begin{bmatrix} e_1^h \\ e_2^h \\ \cdot \\ \cdot \\ \cdot \\ e_N^h \end{bmatrix}}_{\mathbf{e}^h_{(N\times 1)}} = \underbrace{\begin{bmatrix} C_{11}^h & C_{12}^h & \cdots & C_{1M}^h \\ C_{21}^h & C_{22}^h & \cdots & C_{2M}^h \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ C_{N1}^h & C_{N2}^h & \cdots & C_{NM}^h \end{bmatrix}}_{\mathbf{C}^h_{(N\times M)}} \times \underbrace{\begin{bmatrix} A_{11}^h & A_{12}^h & \cdots & A_{1K}^h \\ A_{21}^h & A_{22}^h & \cdots & A_{2K}^h \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ A_{M1}^h & A_{M2}^h & \cdots & A_{MK}^h \end{bmatrix}}_{\mathbf{A}^h_{(M\times K)}} \underbrace{\begin{bmatrix} g_1^h \\ g_2^h \\ \cdot \\ \cdot \\ \cdot \\ g_K^h \end{bmatrix}}_{\mathbf{g}^h_{(K\times 1)}} \tag{1}$$

where:

$$C_{nm}^h = \frac{X_{nm}^{hC}}{\eta_{nm}^{hC}} \tag{2}$$

$$A_{nm}^h = \frac{X_{mk}^{hA}}{\eta_{mk}^{hA}} \tag{3}$$

To investigate the interface between two stages, the vector $\mathbf{l}^h$ can be defined as follows:

$$\mathbf{l}^h_{(M\times 1)} = \mathbf{A}^h_{(M\times k)}\mathbf{g}^h_{(K\times 1)} \tag{4}$$

where $\mathbf{l}^h$ contains the energy that should be provided through the energy converters to supply the appliances. The scope of this paper is HLI and it is required to aggregate the energy demand of all the consumers. To estimate the total loads at the DS (demand side), a similar equation to Eq. (1) is used as follows:

$$\mathbf{e}^{DS}_{(N\times 1)} = \mathbf{C}^{DS}_{(N\times M)}\mathbf{A}^{DS}_{(M\times K)}\mathbf{g}^{DS}_{(K\times 1)} \tag{5}$$

where the vector $\mathbf{e}^{DS}$ represents the total demand of energy carriers that the system should provide and the vector $\mathbf{g}^{DS}$ is the summation of the services demand. If the number of consumers is limited, the parameters and variables are calculated accurately. However, when the number of consumers is large, for each type of consumer a typical services demand profile is assumed and the parameters and variables are estimated based on it. For this purpose, it is assumed that there are Ξ types of consumers (including residential, commercial, industrial and agricultural) and the annual services demand profile is similar for each type. Then, the services demand is estimated as follows:

$$\mathbf{g}^{DS}_{(K\times 1)} = \sum_{\xi=1}^{\Xi} V_\xi \mathbf{g}^{h,\xi}_{(K\times 1)} \tag{6}$$

where V_ξ is the number of the consumers with type ξ and $\mathbf{g}^{h,\xi}$ is the normalized services demand of a typical consumer with type ξ.

$\mathbf{A}^{DS}$is the equivalent appliances matrix for all the demand side consumers. For each DSA (demand side appliance), the corresponding entry in the matrix $\mathbf{A}^{DS}$ and the corresponding dispatch factor of that entry ($X_{m,k}^{DSA}$) are calculated as follows:

$$A_{m,k}^{DS} = \frac{\sum_{h=1}^{H} A_{m,k}^h g_k^h}{\sum_{h=1}^{H} g_k^h} \tag{7}$$

$$X_{m,k}^{DSA} = \frac{\sum_{h=1}^{H} X_{m,k}^{hA} g_k^h}{\sum_{h=1}^{H} g_k^h} \tag{8}$$

where H is the number of all consumers. Similarly to the appliances matrix, an equivalent matrix $\mathbf{C}^{DS}$ is established to represent all DSECs (demand side energy converters). Each entry of the matrix $\mathbf{C}^{DS}$ and its corresponding dispatch factor are calculated as follows:

$$C_{n,m}^{DS} = \frac{\sum_{h=1}^{H} C_{n,m}^h l_m^h}{\sum_{h=1}^{H} l_m^h} \tag{9}$$

$$X_{n,m}^{DSEC} = \frac{\sum_{h=1}^{H} X_{n,m}^{hc} l_m^h}{\sum_{h=1}^{H} l_m^h} \tag{10}$$

where:

$$\mathbf{l}^h_{(M\times 1)} = \mathbf{A}^h_{(M\times k)}\mathbf{g}^h_{(K\times 1)} \tag{11}$$

The equivalent efficiency of each appliance and energy converter is calculated as expressed in Eqs. (12) and (13), respectively.

$$\eta_{m,k}^{DSA} = \frac{X_{m,k}^{DSA}}{A_{m,k}^{DS}} \tag{12}$$

$$\eta_{n,m}^{DSEC} = \frac{X_{n,m}^{DSEC}}{C_{n,m}^{DS}} \tag{13}$$

For the sake of simplicity, it is assumed that the efficiency values are constant with respect to load variations.

2.2. Modeling the multi-carrier demand during the interruption

This subsection presents the process to model the dependency of loads during interruption. In any case of interruption or energy shortage, the consumers will change the set point of the energy converters (e.g., a micro-turbine) or use their extra appliances to gain the potential redundancy of MCESs in reaching the goods, which may result in an increment of uninterrupted energy carriers demand.

To model the usage of extra appliances in the occurrence of curtailment of the energy carrier γ, the matrix $\mathbf{X}_{\gamma}^{EA}$ is defined as follows:

$$\mathbf{X}_{\gamma}^{EA} = \begin{bmatrix} X_{11,\gamma}^{EA} & X_{12,\gamma}^{EA} & \cdots & X_{1K,\gamma}^{EA} \\ X_{21,\gamma}^{EA} & X_{22,\gamma}^{EA} & \cdots & X_{2K,\gamma}^{EA} \\ \vdots & \vdots & \ddots & \vdots \\ X_{M1,\gamma}^{EA} & X_{M2,\gamma}^{EA} & \cdots & X_{MK,\gamma}^{EA} \end{bmatrix} \tag{14}$$

where $X_{mk,\gamma}^{EA}$ is the available dispatch factor for extra appliance m to service k that can be used if the energy carrier γ becomes interrupted. For example, referring to the appliances, if 50% of customers use the gas cooker for cooking in normal condition, and 20% of them use the electric cooker in case of gas curtailment, then $X_{mk,\gamma}^{EA}$ will be 0.1 (20% of 50%) in the corresponding entry of the matrix.

Let us define a parameter $\varepsilon_{mk}^{\gamma}$ to show the utilization factor of extra appliances. This factor indicates, when the energy carrier γ becomes interrupted, what percentage of the available extra appliances m to service k is used in order to substitute energy carrier m instead of γ. This factor depends on the behavior of customers and the curtailment conditions. In order to calculate $\varepsilon_{mk}^{\gamma}$, it is first required to calculate another parameter (q_{mk}^{γ}) as follows:

$$q_{mk}^{\gamma} = \min\left(\frac{X_{mk}^{DSA}}{\sum\limits_{\substack{\delta\in M\\ \delta\neq\gamma}} X_{\delta k,\gamma}^{EA}}, 1\right) \tag{15}$$

This parameter is used to guarantee that the usage of the extra appliance will not be higher than for the appliance in normal condition. For example, if 40% of consumers use hot water for heating their building, the corresponding dispatch factor (X_{mk}^{DSA}) will be 0.4; then according to Eq. (15) in case of hot water shortage, the summation of dispatch factors for extra appliances that are applied to consume other energy carriers instead of hot water should not be higher than 0.4. Thus, the utilization factor of extra appliances is calculated as follows:

$$\varepsilon_{mk}^{\gamma} = \begin{cases} \dfrac{\Delta L_{\gamma}^{DS}}{l_{\gamma}^{DS}} * q_{mk}^{\gamma} & \textit{for } \gamma \in \textit{electricity} \\ \min\left(\dfrac{\Delta L_{\gamma}^{DS}}{\sum\limits_{k\in K}\sum\limits_{\delta\in M} q_{mk}^{\gamma} X_{\delta k,\gamma}^{EA} g_{k}^{DS}}, 1\right) * q_{mk}^{\gamma} & \textit{for } \gamma \in \textit{other carriers} \end{cases} \tag{16}$$

in which Δl_{γ}^{DS} and l_{γ}^{DS} are the amount of energy shortage and total demand for the energy carrier γ. From Eq. (16), if there is a 10% shortage for supplying the electricity demand (Δl_{γ}^{DS} to l_{γ}^{DS} is 0.1), then just 10% of the available extra appliances can be used. That is because in case of 10% electricity shortage, usually 10% of customers become completely interrupted. However, if there is a 10% shortage in gas (or heat) demand, then all customers will feel 10% shortage regarding the low pressure (or temperature) and they can use all their extra appliances to compensate the shortage. Furthermore, the minimum term in Eq. (16) guarantees that the utilization of extra appliances will not be higher than the necessity (the substituted energy will not be more than the energy shortage). Therefore, after an interruption occurrence, by exploiting the extra appliances all entries of the matrix $\mathbf{A}^{DS}$ should be updated based on the new dispatch factors, as follows:

$$X_{mk}^{DSA} = X_{mk}^{DSA} + \sum_{\substack{\gamma\in M\\ \gamma\neq m}} \varepsilon_{mk}^{\gamma} X_{mk,\gamma}^{EA} - \sum_{\substack{\delta\in M\\ \delta\neq m}} \varepsilon_{\delta k}^{m} X_{\delta k,m}^{EA} \tag{17}$$

The first term represents the dispatch factor regarding the normal conditions. The second term represents the exploitation of extra appliances m to provide the service k due to interruption of other carriers γ; and, the third term is developed to calculate the reduction of demand m that has been compensated with other extra appliances δ to provide the service k due to interruption of carrier m.

On the other hand, in any case of interruption, the consumers change the set points of the energy converters and therefore, the dispatch factor of the energy converters will be changed. In order to model the set point variation, the power capacity of the energy converters is represented in a matrix as follows:

$$\varsigma_{(N\times M)}^{DSEC} = \begin{bmatrix} \varsigma_{11}^{DSEC} & \varsigma_{12}^{DSEC} & \cdots & \varsigma_{1M}^{DSEC} \\ \varsigma_{21}^{DSEC} & \varsigma_{22}^{DSEC} & \cdots & \varsigma_{2M}^{DSEC} \\ \vdots & \vdots & \ddots & \vdots \\ \varsigma_{N1}^{DSEC} & \varsigma_{N2}^{DSEC} & \cdots & \varsigma_{NM}^{DSEC} \end{bmatrix} \tag{18}$$

Based on this matrix, the output power of each energy converter should satisfy the following constraint:

$$X_{n,m}^{DSEC} l_{m}^{DS} \leq \varsigma_{n,m}^{DSEC} \tag{19}$$

In this equation, the left term demonstrates the power that is converted through converter n to supply load m. Further description of the energy converter modeling during the energy curtailments is provided in Section 3.

2.3. Conventional units modeling of the generation system

As mentioned, in adequacy evaluation of power systems, a COPT (Capacity Outage Probability Table) is established based on forced outage rate of each power plant [1]. However, in a MCES, each block that is shown as a resource or GSEC (generation side energy converter) in Fig. 1, itself may be a representative of several units. For example, the GSEC that represents the conversion of natural gas to electricity includes many gas-fired power plants. Or, natural gas resource is representative of several natural gas processing plants. Therefore, it is required to establish a COPT for each resource and GSEC. It can be noted that even though the GSECs and DSECs are physically similar, they are considered at two different stages and with different models. The main difference between the GSECs and DSECs is that GSECs are operated under the system operator supervision, while the operation of DSECs is autonomous. In addition, since usually the reliability indices are calculated at the load points, it is required to consider the elements of generation side and demand side separately. However, for a system that is not large (e.g., a small micro-grid) and in which all converters are operated under the system operator supervision, the energy converters modeling at generation side and demand side can be composed of only one stage, and the reliability indices will be calculated at the point between converters and appliances.

Assume that a resource block or a GSEC block has Y units, then its corresponding COPT will have $Z = 2^Y$ states, and the limiting probability of each state z, can be obtained as follows [1,22]:

$$p_z = \prod_{y=1}^{Y} \left(\rho_{y,z} \cdot R_y + \left(1 - \rho_{y,z}\right) \cdot Q_y \right) \tag{20}$$

where, $\rho_{y,z}$ is a binary variable which is 1 when unit y is an operating unit in state z and is 0 when the unit is a failing unit. Moreover, R_y is the limiting probability of success for unit y with failure rate of λ_y and repair rate of μ_y and can be calculated as follows [1,22]:

$$R_y = \frac{\mu_y}{\mu_y + \lambda_y} \tag{21}$$

In addition, Q_y is the failure probability of the corresponding unit, which is also called FOR (forced outage rate) and is equal to $(1 - R_y)$.

For each state, the available power capacity is the summation of operating units capacity and it will be used as a maximum limitation in problem constraints. For resource j or energy converter j to output n it is represented as ς_j^S and $\varsigma_{j,n}^{GSEC}$, respectively. For example, if the available capacity of the gas-fired system supplying electricity is $\varsigma_{gas,\ electricity}^{GSEC}$, the associated limitation for this energy converter is as follows:

$$X_{gas,electricity}^{GSEC} e_{gas} \le \varsigma_{gas,electricity}^{GSEC} \tag{22}$$

2.4. Modeling the multi-input and multi-output energy converters

There are some energy converters that can be supplied by more than one type of energy. For example, there are some power plants that can be supplied either by gas or diesel. A method is discussed here to consider these multi-input energy converters. The presented method is global and it can be used for both DSECs and GSECs. Let us assume that in a system the capacity of power plants which can be supplied only by gas is 900 kW and the capacity of power plants which can be supplied only by diesel is 400 kW. Moreover, there are a capacity of 600 kW that can be supplied with both gas and diesel. Then, to consider these multi-input energy converters in the problem, the capacity constraints are defined as follows:

$$\varsigma_{gas,electricity}^{GSEC} = 900 + 600\ \ kW \tag{23}$$

$$\varsigma_{oil,electricity}^{GSEC} = 400 + 600\ \ kW \tag{24}$$

$$\varsigma_{gas,electricity}^{GSEC} + \varsigma_{oil,electricity}^{GSEC} = 400 + 900 + 600\ \ kW \tag{25}$$

For considering multi-output energy converters (e.g., CHP) in modeling it is required to define new dispatch factors. For example, let us assume that besides the individual energy converters for converting gas to electricity and the energy converters for converting gas to heat, there is an installed capacity of CHP. It is assumed that the first input carrier of DSECs is gas, and the first and the second loads are electricity and heat, respectively. Moreover, it is assumed that the output heat of CHP should be 1.5 times the electricity output. Then, the dispatch factor in this case is defined as follows:

$$\mathbf{X}^{DSEC} = \begin{bmatrix} X_{11}^{DSEC} + \dot{X}_{11}^{DSEC} & X_{12}^{DSEC} + \dot{X}_{12}^{DSEC} & \cdots & X_{1M}^{DSEC} \\ X_{21}^{DSEC} & X_{22}^{DSEC} & \cdots & X_{2M}^{DSEC} \\ \vdots & \vdots & \ddots & \vdots \\ X_{N1}^{DSEC} & X_{N2}^{DSEC} & \cdots & X_{NM}^{DSEC} \end{bmatrix} \tag{26}$$

where $\dot{X}_{11}^{DSEC}$ and $\dot{X}_{12}^{DSEC}$ are defined to represent the dispatch factor of the multi-output energy converter (CHP), and a constraint will represent the supposed relation of them. For the mentioned example, this constraint will be as follows:

$$1.5\,\dot{X}_{11}^{DSEC} l_1^{DS} - \dot{X}_{12}^{DSEC} l_2^{DS} = 0 \tag{27}$$

Similar dispatch factors can be defined for other matrix entries if there are also multi-input energy converters.

2.5. Renewable generation modeling

Similar to conventional units, the multi-state COPT model is also used to model generation from renewable resources. This model has been widely adopted in power system planning studies [23]. This COPT model represents the generation of renewable resources with W states and each state w is expressed as (ζ_w^r, p_w^r), where ζ_w^r is the average power capacity in the wth state, and p_w^r is the occurrence probability of that state. The probability of each state is calculated considering the stochastic behavior of renewable resources (e.g., wind speed, sun radiation) and forced outage rate of the elements. However, these calculations and establishment of the renewable COPT is without the scope of this paper and is described completely in Ref. [23]. In this paper, it is assumed that the multi-state COPT model of renewable generation is prepared and it is used as the input of the problem.

3. Adequacy evaluation procedure

Presented studies for adequacy evaluation of electric generation systems establish and calculate the reliability indices considering the LDC (Load Duration Curve) [1]. However, in our problem, it is not possible to use LDCs, because for a load level of one energy carrier (e.g., electricity), it may be different load levels of other carriers (e.g., gas), and thus, converting load curves into LDCs will put down the coincidence of the load levels during the time and the mutual dependence of loads cannot be investigated. Therefore, the evaluation process is implemented for all periods (hours) of a year and for each period, all the states of generation system are investigated. Two well-known indices, *LOLP* (Loss of load probability) and *EENS* (Expected energy not supplied) are considered and calculated.

The energy demand in normal conditions is calculated for each period by using Eq. (5). Moreover, implementing the presented COPT modeling of subsections (2.3), (2.4) and (2.5), the capacity of each connection in each state and its corresponding probability is determined. If there are Φ blocks for conventional resources and GSECs in Fig. 1 and each block ϕ has Z_ϕ states, and also there are B types of renewable resources and for each type of b there are W_b states, then convolving these states, the number of all possible generation system states is calculated as follows:

$$Z = Z_1 \times \ldots \times Z_\Phi \times W_1 \times \ldots . \times W_B \tag{28}$$

To decrease the dimension of the problem, the states with very small probability will be neglected.

The evaluation procedure of a state during a period is discussed in the next subsections. Two scenarios are considered; in the first scenario, the substitution potential of loads in demand side during the interruption is not considered and indices are calculated based on the loads of the demand side in normal condition; the focus of this scenario is set on considering the limitation of primary resources. In the second scenario, the variation of set point on the energy converters and the application of extra appliances during the interruptions are considered.

3.1. Scenario I: considering the limitation of energy resources and allocating the primary resources to different energy infrastructures

It is assumed that demand of different energy carriers at the demand side ($\mathbf{e}^{DS}$) is determined. This demand vector can be determined based on the proposed model as expressed in Eq. (5) or it can also be forecasted like the traditional system. Considering the available capacity of connections in each state and the limitation of primary resources, the available energy resources are assigned to the connections in order to supply energy demand. If there is any leakage for primary resources, the energy demand will not be supplied completely. However, the available resources are assigned in a way that maximum valuable energy becomes supplied. For example, in case of natural gas shortage as a primary resource, if electricity is a priority, first the electricity demand will be supplied, and then the residual gas will be assigned to the other energy demands.

To consider the priority of different energy infrastructure supply, it is possible to consider the cost of load interruption π_n for each carrier n and assign the resources based on it. However, it is possible to assume that interruption cost is the same for all energy carriers and just restore maximum energy, neglecting the priority. Anyway, the total cost of interruption can be formulated as follows:

$$\Pi = \sum_{n=1}^{N}\left[\left(e_n - \sum_{j=1}^{J} X_{j,n} e_n\right)\pi_n\right] \tag{29}$$

where, $X_{j,n}$ is the proportion of nth energy carrier demand that is supplied by resource j through GSEC j to output n. This function should be minimized, and thus, it is an optimization problem that should be done to find the loads not supplied. As it is required to run this model for every state and time period, it is formulated as a linear program which can be solved quickly. By deleting the constant term of E_n and multiplying the number -1, the resources allocation problem is formulated as follows:

$$\max f = \sum_{n=1}^{N}\sum_{j=1}^{J} X_{j,n} e_n \pi_n \tag{30.a}$$

subject to:

$$\sum_{n=1}^{N} \frac{X_{j,n}^{GSEC} e_n^{DS}}{\eta_{j,n}^{GSEC}} \le \varsigma_j^{S} \tag{30.b}$$

$$X_{j,n}^{GSEC} e_n \le \varsigma_{j,n}^{GSEC} \tag{30.c}$$

$$\sum_{n=1}^{N} X_{j,n}^{GSEC} \le 1 \tag{30.d}$$

$$0 \le X_{j,n}^{GSEC} \le 1 \tag{30.e}$$

After solving the linear programming problem, if the summation of any column of matrix $\mathbf{X}^{GSEC}$ is not equal to one, it means that some energy demand has not been supplied. To find the energy not supplied of each carrier n, Eq. (31) is utilized:

$$\Delta e_n = e_n - \sum_{j=1}^{J} X_{j,n} e_n \tag{31}$$

3.2. Scenario II: considering DSECs set point variation and extra appliances deployment

In the case of energy shortage, the set point of DSECs is changed and extra appliances are deployed in order to supply the loads through other energy carriers. For this purpose, first the set point variation of DSECs is obtained, then the application of extra appliances is considered.

In order to find the new set point of DSECs, the mentioned allocation process in the previous subsection is done, and then based on Eq. (31), the networks with interruption are determined. The available energy of interrupted network is set to be equal to the obtained amounts from Eq. (31), and then, similar to Eq. (30), another allocation process is done to find the new set point of DSECs and allocate the available energy through the DSECs:

$$\max f = \sum_{m=1}^{M}\sum_{n=1}^{N} X_{n,m}^{DSEC} l_m^{DS} \pi_m \tag{32.a}$$

subject to Eq. (19) and:

$$\sum_{m=1}^{M} \frac{X_{n,m}^{DSEC} l_m^{DS}}{\eta_{n,m}^{DSEC}} \le \overline{e}_n^{DS} \tag{32.b}$$

$$\sum_{m=1}^{M} X_{n,m}^{DSEC} \le 1 \tag{32.c}$$

$$0 \le X_{n,m}^{DSEC} \le 1 \tag{32.d}$$

where π_m is the interruption cost of energy carrier m and it is defined to consider the priority of loads supply. Moreover, Eq. (32.b) is used to consider the supply limitation of interrupted networks and $\overline{e}_n^{DS}$ is determined using Eq. (31) for interrupted networks and it is infinity for uninterrupted networks. If the summation of all columns of matrix $\mathbf{X}^{DSEC}$ is equal to one, it means that all loads are supplied by the new set point of DSECs; otherwise, it is required to consider the extra appliances as mentioned in subsection (2.2).

Based on new obtained dispatch factor of DSECs and appliances, energy demand ($\mathbf{e}^{DS}$) will change. Therefore, it is required to investigate Eq. (30) again. If this variation leads to energy curtailment in a new infrastructure, again this process will be repeated. It should be considered that since the number of energy carriers in the real world is not large, the computational burden of these analyses is not an issue.

For both scenarios, for each state and during each period, the amount of energy not supplied and the probability of loss of load occurrence are calculated.

4. Numerical results and discussion

In this section a test system (Fig. 3) is used to show the effectiveness of the presented modeling approach. The initial resources

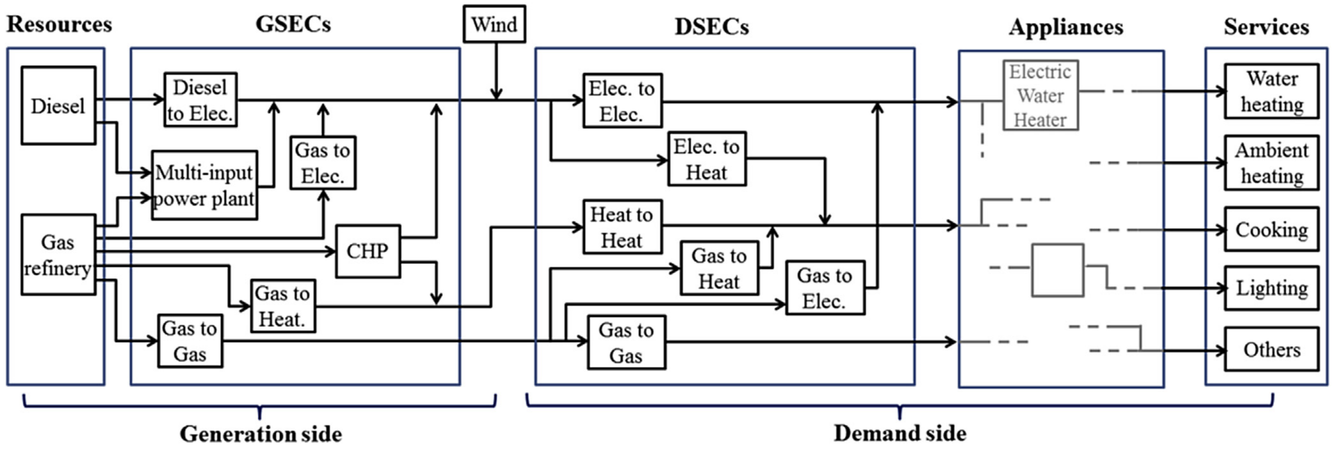

Fig. 3. The test system used in simulations.

of the system are assumed to be diesel and gas. The gas resource is provided through two 10-MW gas refinery units and the maximum available capacity of diesel is considered to be 2 MW. There are several resources and energy converters in the generation side as shown in Table 1 to provide three energy infrastructures: electricity, gas and heat. Moreover, a CHP (capacity of gas to electricity 800 kW, capacity of gas to heat 1000 kW, Power to Heat Ratio 0.8, failure rate 1 failure per year, repair time 8 h) is assumed to be installed at the generation side. A wind turbine with a 5-state model as shown in Table 2 is also considered. In the test system used, the capacity of the wind generation is 400 kW. A five-state model has been indicated to be appropriate for modeling wind power generation system with an acceptable approximation, also for larger wind power capacity [23,24].

The capacity of the DSECs is provided in Table 3; the designed capacity of direct links (e.g. gas to gas) is assumed to be sufficient for all simulated cases, thus, no limitation is considered for them. The conversion factors of DSECs in normal conditions are shown in Table 4. Table 5 contains the conversion factors of the appliances in normal conditions and during the interruption of energy infrastructures. All conversion factors are dimensionless. A 24-h period is considered for simulating the proposed models. It should be considered that usually the adequacy analysis is done for a yearly period and in this section a daily period is considered just to show the effectiveness of the presented models. The demand of services during the time horizon is shown in Fig. 4.

Two scenarios have been simulated. In the first scenario, the mutual dependence of loads at demand side is neglected and the indices are calculated based on the proposed method for the generation side. For each hour, the energy not supplied and the probability of loss of load are determined. The results of the first scenario are shown in Figs. 5 and 6. Most of the contributions to the *LOLP* and *EENS* of each energy carrier belong to the time interval from hour 19 to hour 22, in which the demand of energy is high. As it can be seen from the results, although there is no correlation between the variations of energy services demand in Fig. 4, the variations of the obtained indices for the energy carriers are consistent. The reason is that the energy carriers are supplied from the same primary resources and can be converted into each other through different energy converters, thus high consumption of one energy carrier will affect other carriers too.

In the second scenario, it is assumed that the consumers use their extra appliances and energy converters in order to supply the maximum load during any interruption occurrence. The results obtained for the whole day are presented in Table 6 regarding two simulated scenarios. As it can be seen, for the presented test system, electricity has the largest *LOLP* and *EENS*. The results of Table 6 show that when the substitution potential of loads at the demand side is considered, all the indices have been improved. This improvement is 55% for the *total EENS*. Fig. 7 shows the calculated total *EENS* of all three energy carriers for each hour of the day

Table 2
Five-state model of wind generation.

Probability	0.25	0.15	0.35	0.1	0.15
Output power (kW)	0	100	200	300	400

Table 3
The capacity of demand side energy converters (kW).

From	To		
	Electricity	Gas	Heat
Electricity	–	0	750
Gas	2250	–	3000
Heat	0	0	–

Table 1
The data of the generation side energy converters and resources.

	Resources	Generation side energy converters		
	Gas refineries	Electric power plants		Heaters
	Raw natural gas to fuel gas	Gas to electricity	Gas or diesel to electricity	Gas to heat
Power Capacity (kW)	2 × 10 000	4 × 1250	2 × 1500	2500
Repair time (hour)	8	160	16	8
Failure rate (failure per year)	2.5	7.5	5	1

Table 4
Conversion factors of the demand side energy converters in normal conditions for 24 h.

From	Electricity			Gas			Heat		
To	Electricity	Gas	Heat	Electricity	Gas	Heat	Electricity	Gas	Heat
1	0.9	0	0.1	0.1	1	0.3	0	0	0.6
2	1	0	0.1	0	1	0.3	0	0	0.6
3	1	0	0.1	0	1	0.3	0	0	0.6
4	1	0	0.1	0	1	0.3	0	0	0.6
5	1	0	0.1	0	1	0.4	0	0	0.5
6	1	0	0.1	0	1	0.4	0	0	0.5
7	0.9	0	0.1	0.1	1	0.4	0	0	0.5
8	0.85	0	0.05	0.15	1	0.4	0	0	0.5
9	0.75	0	0.05	0.25	1	0.45	0	0	0.5
10	0.7	0	0.05	0.3	1	0.45	0	0	0.5
11	0.7	0	0.05	0.3	1	0.45	0	0	0.5
12	1	0	0	0	1	0.4	0	0	0.6
13	1	0	0	0	1	0.4	0	0	0.6
14	1	0	0	0	1	0.4	0	0	0.6
15	1	0	0	0	1	0.4	0	0	0.6
16	1	0	0	0	1	0.4	0	0	0.6
17	0.8	0	0.05	0.2	1	0.4	0	0	0.55
18	0.75	0	0.05	0.25	1	0.45	0	0	0.5
19	0.8	0	0.05	0.2	1	0.45	0	0	0.5
20	0.8	0	0.05	0.2	1	0.45	0	0	0.5
21	0.8	0	0.05	0.2	1	0.45	0	0	0.5
22	0.8	0	0.05	0.2	1	0.45	0	0	0.5
23	0.8	0	0.1	0.2	1	0.45	0	0	0.45
24	0.9	0	0.1	0.1	1	0.5	0	0	0.4

Table 5
Conversion factors of appliances in normal conditions and during the energy carrier interruptions.

		Cooking	Lighting	Ambient heating	Water heating	Others (electric appliances)
Normal conditions	Electricity	0.2	1	0.1	0	1
	Gas	0.8	0	0.4	0.5	0
	Heat	0	0	0.5	0.5	0
Electricity interruption	Electricity	0	0	0	0	0
	Gas	0.05	0.01	0.04	0	0
	Heat	0	0	0.04	0	0
Gas interruption	Electricity	0.02	0	0.02	0	0
	Gas	0	0	0	0	0
	Heat	0	0	0.05	0.1	0
Heat interruption	Electricity	0	0	0.02	0	0
	Gas	0	0	0.06	0.08	0
	Heat	0	0	0	0	0

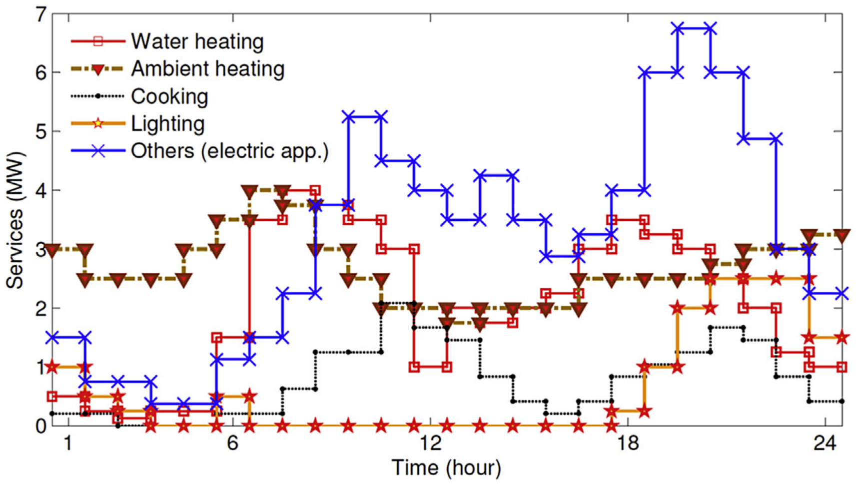

Fig. 4. The demand of energy services for a daily period.

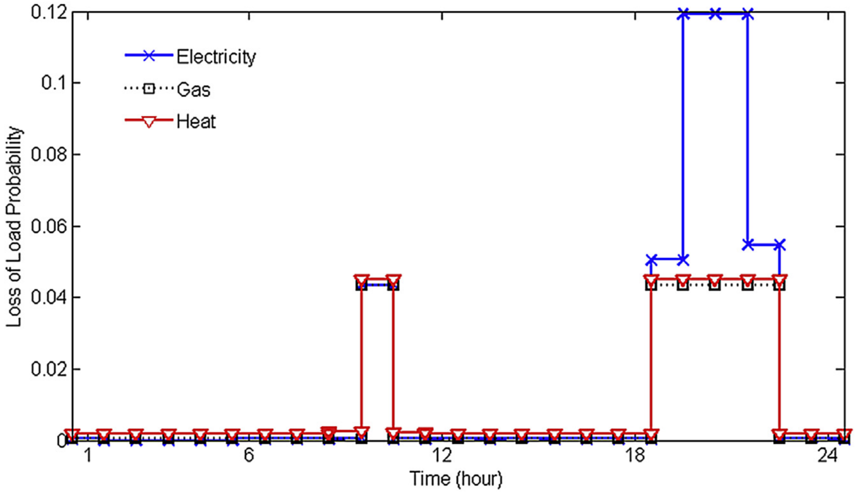

Fig. 5. The calculated *LOLP* during each hour of a daily period for three energy carriers.

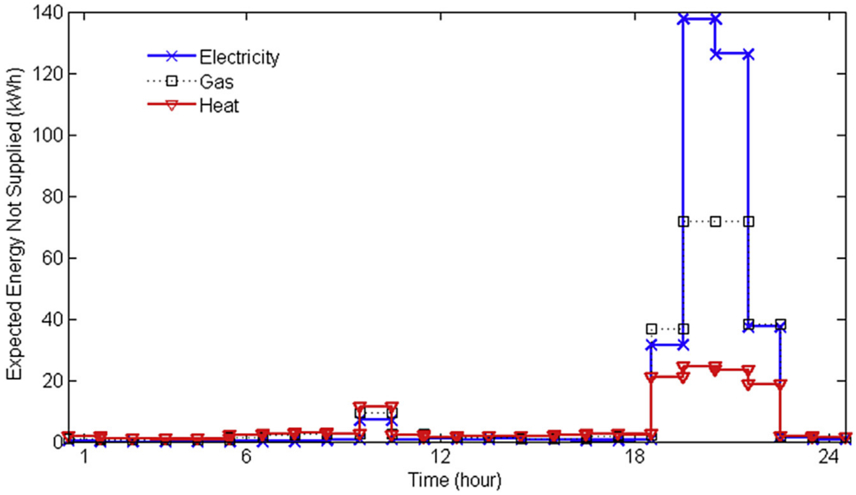

Fig. 6. The calculated *EENS* during each hour of a daily period for three energy carriers.

Table 6
The calculated adequacy indices considering two scenarios (*EENS* in kWh).

	LOLP Electricity	*LOLP* Gas	*LOLP* Heat	*EENS* Electricity	*EENS* Gas	*EENS* Heat	Total *EENS*
Scenario I	0.0164	0.0094	0.0110	348.78	255.61	132.51	736.90
Scenario II	0.0116	0.0036	0.0107	225.70	68.59	38.61	332.90

considering both scenarios. As it can be seen from the figure, the calculated *EENS* from the second scenario is better for all the hours.

For the presented results (Table 6) it was assumed that the costs of load interruption for all energy carriers are equal. In the following, the simulation process is repeated with the assumption that the priority of electricity supply is higher than for the other carriers. Let us consider that the interruption costs of electricity are twice the interruption costs of the other energy carriers. As shown in Table 7, the calculated indices for the electricity system have been improved if compared with the results of Table 6. However, in this case the total *EENS* has been increased in comparison with the results of Table 6. Similar results are obtained for the cases that the priority of gas or heat is assumed more than other loads as shown in Table 7. For the cases in which the heat has the first priority of supply, even the obtained *LOLP* and *EENS* of heat in both scenarios have been improved in comparison to the results of Table 6, the obtained index *LOLP* in scenario II is 0.0071, which is worse than the *LOLP* 0.0020 obtained in the scenario I. The reason is that applying the demand side energy converters and extra appliances during curtailment of one energy infrastructure (here, electricity or gas) can result in increment of other forms of loads and may propagate curtailment to another energy infrastructure (here, heat). Therefore, in some cases the obtained *LOLP* in scenario II can be worse than the one in scenario I.

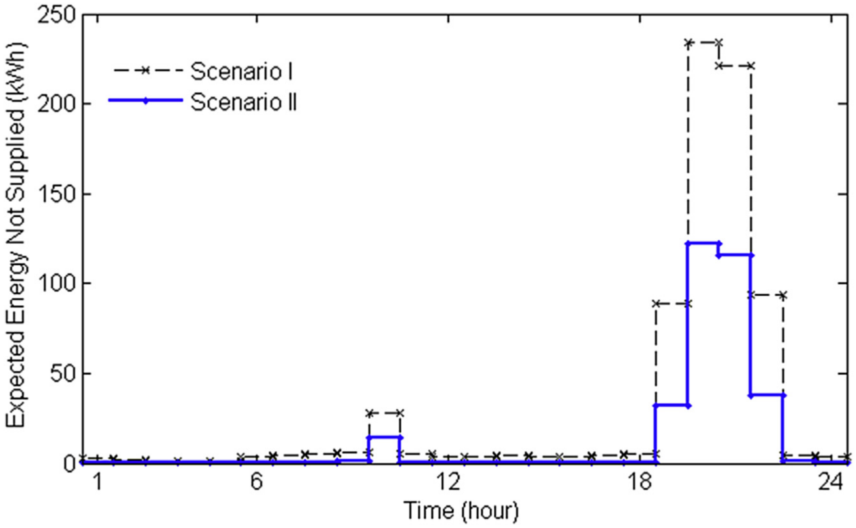

Fig. 7. The calculated total *EENS* during each hour of a daily period considering two different scenarios.

Table 7
The calculated adequacy indices considering the priority of supply of one energy carrier more than the others (*EENS* in kWh).

		LOLP Electricity	*LOLP* Gas	*LOLP* Heat	*EENS* Electricity	*EENS* Gas	*EENS* Heat	Total *EENS*
First priority:	Scenario I	0.0077	0.0094	0.0110	179.63	414.13	143.15	736.90
Electricity	Scenario II	0.0077	0.0092	0.0066	144.88	155.17	93.48	393.54
First priority:	Scenario I	0.0164	0.0004	0.0110	539.43	40.37	157.11	736.91
Gas	Scenario II	0.0146	0.0004	0.0110	310.87	$<10^{-2}$	85.43	396.30
First priority:	Scenario I	0.0164	0.0094	0.0020	386.02	305.18	45.69	736.90
Heat	Scenario II	0.0095	0.0073	0.0071	203.66	144.71	20.29	368.66

5. Conclusion

This paper has presented a new way to model the adequacy of an energy system considering multi-energy carriers at both generation and demand sides, setting the focus on the provision of energy services.

Two scenarios have been modeled and simulated. The first scenario considered the generation side and assumed that there is no dependency between the demand of energy carriers. The second scenario assumed that in case of interruption, consumers can benefit from their energy converters and deploy extra appliances to provide the energy services demand through other energy carriers. The main outputs of this study are as follows:

1 It is required to consider the power capacity limitation of the primary energy resources in the generation system adequacy study.
2 In case of energy shortage, determining different interruption costs for different energy carriers resulted in different adequacy indices.
3 In most of the time, the substitution capability of the energy carriers at the demand side improves the reliability indices.
4 In some cases, the substitution capability of energy carriers can propagate the interruption from one energy infrastructure to another, thus worsening the obtained indices for the other carrier.

The models presented in this paper can be applied to planning studies and provide results useful for the assessment of long-term investment strategies associated with the development of multi-carrier energy systems.

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