Optimal Operation of Multi-Carrier Energy Networks Considering Uncertain Parameters and Thermal Energy Storage

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Received: 19 May 2020; Accepted: 13 June 2020; Published: 24 June 2020

Abstract: The coordination of energy carriers in energy systems has significant benefits in enhancing the flexibility, efficiency, and sustainability characteristics of energy networks. These benefits are of great importance for multi-carrier energy networks due to the complexity of obtaining optimal dispatch, considering the non-convex nature of their energy conversion. The current study proposes a robust operation model for the coordination of multi-carrier systems, including electricity, gas, heat, and water carriers concerning thermal energy storage technology. Thermal energy storage is for storing extra heat generated by combined heat and power (CHP) plants and boilers in time intervals with low heat demand on the system and discharging it when required. Energy network operators should have the capability to manage uncertain energy loads to study the impact of load variation on the decision-making process in network operation. Accordingly, this study employs an information gap decision theory (IGDT) method to model the uncertainty of the power demand in optimal system operation. By applying the IGDT approach, the operator of the energy system can use the appropriate methodology to obtain a robust optimal operation. Such a modeling approach helps the operator to make suitable decisions about probable variations in power load. The introduced model is applied in a test system for evaluating the performance and effectiveness of the introduced scheme.

Keywords: multi-carrier energy network; thermal energy storage technology; information gap decision theory; load uncertainty; robust decision-making; energy efficiency

1. Introduction

In 2013, Presidential Policy Directive 21 (PPD-21) introduced the energy section as a critical element, considering its role in supplying necessary functions across all fundamental infrastructures. The importance and complexity of the interdependencies between energy carriers have long been established. As there are untapped synergies and complementary characteristics of different energy carriers, these energy networks are physically interconnected and they can be studied as an integrated network. However, energy networks have been studied with de-coupled characteristics in traditional models from both planning and operational perspectives, and only narrow interactions among energy networks have been considered in recent studies. The integration of energy systems has a positive impact on high efficiency rates and minimizing operating costs. Combined heat and power (CHP) plants can produce heat and power, simultaneously, and increase the power and heat supply efficiency to up to 90%. CHP plants can also reduce the emissions of pollutant gases by almost 13–18%. Obtaining
optimal operating setpoints of the generation plants in energy systems is of great importance and has been studied in several studies [1–3].

Recent literature in the area of integrated energy networks can be divided into two categories. First, researchers have investigated the role of disruptions and uncertainties in integrated networks. Some studies have introduced security-constrained models for gas and power networks to investigate the influence of interruptions in gas/power systems [4,5] or robust models to analyze the adjustment of the power load considering uncertainties associated with the power output of renewable energy sources [6,7]. In [8], a unit commitment (UC) is presented for CHP networks and district heating networks (DHN) in existing CHP plants, where the effect of heat storage is evaluated. A risk investigation of integrated heat and power networks is performed to determine the uncertainties of power market price and wind power output in [9]. In [10], the authors have used the robust model to evaluate the uncertainty of load on the scheduling of multi-chiller systems, where a day-ahead scheduling scheme is proposed to satisfy the cooling load. In [11], an optimal robust energy management scheme for such systems has been introduced to handle the uncertain parameters of the problem, including the market price and the load of the system.

In other work, researchers concentrated on studying the beneficial/environmental challenges in integrated networks. In integrated gas and power networks, some studies have proposed bi-level programming to deal with the benefits of gas/power systems in one of the levels [12–14]. A bi-level framework is presented in [12], where the upper/lower levels have focused on handling the constraints of power and gas systems. In [13], the researchers considered two conflicting aims for the operation of power and gas systems, including reductions in cost and pollutant gas emission. A bi-level model that studies the planning and operation of such networks in upper/lower levels has been proposed in [14]. The authors in [15] have proposed a robust model for dealing with the uncertainty of power market prices when managing CHP networks. A bi-level model for these systems is presented in [16] to maximize the benefit for operators/CHP owners in the upper/lower levels. In [17], a deterministic network-constrained optimal generation schedule of integrated heat and power systems is investigated. The authors in [18] have proposed a methodological scheme for investigating multi-carrier energy grid designs systematically by involving stakeholders and technical and economic viewpoints. The effect of storage capacity and prediction horizon on the operation cost of these systems is analyzed for a single-family house and a system of houses in [19].

The authors have proposed a steady-state energy flow for multi-carrier networks, including integrated power and gas systems in [20]; interconnected power and heating systems in [21]; and combined power, gas, and heating systems in [22]. An approximated flow scheme is proposed in [23] to obtain the optimal setpoints of the energy system units. The characteristics and advantages of the energy hub concept, which is only capable of handling energy hubs with the same number of inputs and outputs, and the solution to optimal energy flow in multi-carrier systems are studied in [24]. To overcome the shortage of such methods in handling irregular equations in the optimal operation of the multi-carrier system, the authors have presented a scheme using dummy variables and virtual units in [25], which also causes a complex optimization problem due to the additional variables and various complementary constraints. In [26,27], a novel methodology based on the suitable set selection of state-variables for the optimal operation of such a system is proposed with the ability to stop the increase in new variables when converting irregular equations into regular equations. The authors implemented an information gap decision theory (IGDT)-based uncertainty-handling method to handle load uncertainty in the optimal operation of an energy hub with batteries, photovoltaic cells, and fuel cells in [28]. The authors in [29] proposed a multi-objective scheme for the two-stage optimal operation of combined power and gas systems with emerging technologies, such as power to gas plants and demand-side management.

Table 1 compares the contributions of the presented robust operation model with models from the literature. To the best knowledge of the authors, none of the studied papers have investigated an uncertainty study of multi-carrier networks with gas, power heating, and water energy carriers.
using a robust model. The main drawbacks of the reviewed studies are that a robust operation model for systems with all of these carriers is not accomplished and the performance of the whole network is not studied. This study presents an IGDT-based robust operation model for multi-carrier energy networks that considers the role of thermal storage facilities in managing the heat generation schedule of the CHP plant, and the heat load supply of the system is investigated. By using the proposed robust model, the energy network operator should be able to manage the uncertain electrical energy load. Therefore, the IGDT approach is applied in this paper to model the uncertainty of the power demand in multi-carrier networks based on opportunity and robustness functions. The introduced robust model has been implemented in test multi-carrier networks for the evaluation of the performance of the presented scheme.

| Reference | Type of Energy Carriers | UC Problem | Modeling Networks Constraints | Modeling Uncertain Parameter | The Implemented Uncertainty-Handling Method |
|-----------|-------------------------|------------|-------------------------------|-----------------------------|----------------------------------|
| [8]       | Power and heat          | ✓          | ✓                             | -                           | -                                |
| [9]       | Power and heat          | -          | -                             | ✓                           | Stochastic                       |
| [10]      | Power and heat          | -          | -                             | ✓                           | Robust-stochastic                |
| [11]      | Power and gas           | -          | -                             | ✓                           | -                                |
| [12]      | Power and gas           | -          | -                             | ✓                           | -                                |
| [28]      | Power, gas, and heating | ✓          | ✓                             | ✓                           | Two-stage stochastic             |
| [22]      | Power, gas, and heating | -          | ✓                             | ✓                           | IGDT                             |
| [29]      | Power, gas, and heating | ✓          | ✓                             | ✓                           | IGDT                             |

2. Materials and Methods

The framework of the presented robust scheduling of the multi-carrier energy systems is demonstrated in Figure 1, which is based on using the IGDT approach to deal with the uncertainty of the power load. The presented model is for a system with gas, power, heat, and water demands, for which a case study will be selected for evaluating the presented model. The main methodology of the proposed model is considering the uncertainty of power load when scheduling the generation of plants and the charge/discharge operation of the storage units based on the IGDT method. Hence, the total minimized operation cost of the whole energy system based on the optimal set points of the units will be determined. The problem formulation of the system operation in deterministic conditions and with an uncertain status is provided in this section using the IGDT approach.

2.1. Objective Function

The objective of the optimal operation of multi-carrier networks considering power, gas, heat, and water carriers is minimizing the total cost of the supplying energy loads, which is formulated in (1). The first and second terms of (1) are the operation cost of non-gas-fired units considering power supply and start/shut-down and the purchased gas cost from suppliers. The operation cost of the gas storage is given as the third term of (1). It is worth mentioning that the operation cost of gas-fueled units is considered in the second term of (1), since they consume gas to produce electrical energy. Nomenclature is given in Table A1.

\[
O = \min \sum_{t=1}^{T} \left[ \sum_{n=1}^{NE} \left[ F(P_{n,t}) + SU_{n,t} + SD_{n,t} \right] + \sum_{g=1}^{NW} \rho_{gas} GW_{g,t} + \sum_{gs=1}^{NGS} C_{gs} GS_{gs,t} \right]
\] (1)
2.1. Objective Function

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\[
\begin{align*}
    &I_{n,t} \leq I_{n,t} \leq I_{n,t}^\text{max} \\
    &P_{n,t} - P_{n,t}^A - \frac{P_n^A - P_n^\text{th}}{H_n^A - H_n^B} \times (H_{n,t} - H_n^A) \leq 0 \quad n \in \text{NC} \\
    &P_{n,t} - P_{n,t}^A - \frac{P_n^A - P_n^\text{th}}{H_n^A - H_n^B} \times (H_{n,t} - H_n^A) \leq 0 \quad n \in \text{NC} \\
    &P_{n,t} - P_{n,t}^A - \frac{P_n^A - P_n^\text{th}}{H_n^A - H_n^B} \times (H_{n,t} - H_n^A) \geq -(1 - I_{n,t}) \times M \quad n \in \text{NC}
\end{align*}
\]

2.2. Power Network Constraints

The unit commitment constraints of the generation units in the multi-carrier network are discussed in this sub-section. The CHP plant has been considered for supplying power and heat demands, for which the generated heat and power have a mutual dependency, known as the feasible operation region (FOR), as demonstrated in Figure 2. Linear equations of the FOR of the CHP plant are used to limit the generated power and heat by the CHP plant [31].

Figure 1. The presented framework for the robust scheduling of multi-carrier energy networks.

### Nomenclature

- \( I_{n,t} \): Power load
- \( P_{n,t} \): Power generation
- \( P_{n,t}^A \): Power generation of the CHP
- \( P_n^A \): Power generation of the CHP
- \( P_n^\text{th} \): Power consumption of the CHP
- \( H_n^A \): Heat production of the CHP
- \( H_n^B \): Heat consumption of the CHP
- \( H_n^C \): Heat consumption of the CHP
- \( M \): Constraint multiplier
The power balance of the multi-carrier system should be considered for ensuring the balance between the power generation of the CHP plant and conventional power generation systems as well as the power load of the system. Such balance can be formulated as (18). Moreover, the power

\[
P_{n,t} - P_{n,t-1} \leq R_{n,t}^{up}
\]

(8)  

\[
P_{n,t-1} - P_{n,t} \leq R_{n,t}^{dn}
\]

(9)  

\[
I_{i,t} - I_{i,t-1} \leq I_{i,t} + TU_{i,u}
\]

(10)  

\[
TU_{i,u} = \begin{cases} 
    u & \text{if } u \leq MUT_i \\
    0 & \text{if } u > MUT_i
\end{cases}
\]

(11)  

\[
I_{i,t-1} - I_{i,t} \leq 1 - I_{i,t} + TD_{i,u}
\]

(12)  

\[
TD_{i,u} = \begin{cases} 
    u & \text{if } u \leq MDT_i \\
    0 & \text{if } u > MDT_i
\end{cases}
\]

(13)  

The start-up/shut-down costs of the plants, which should be considered for both gas-fired and non-gas-fueled plants, are studied in the model. Such costs for the non-gas-fueled units are as (14)–(15), and the costs for gas-fired plants are as (16) and (17).

\[
SU_{n,t} \geq s_u(I_{n,t} - I_{n,t-1}) \quad n \in NE
\]

(14)  

\[
SD_{n,t} \geq s_d(I_{n,t-1} - I_{n,t}) \quad n \in NE
\]

(15)  

\[
SUG_{n,t} \geq s_{gu}(I_{n,t} - I_{n,t-1}) \quad n \in NGC
\]

(16)  

\[
SDG_{n,t} \geq s_{gd}(I_{n,t-1} - I_{n,t}) \quad n \in NGC
\]

(17)
transmission losses and the limitations of power flow through the system can be presented as (19) and (20), respectively.

\[
\sum_{n=1}^{NU_b} P_{n,t} + \sum_{e=1}^{NES_b} (P_{e,t}^D - P_{e,t}^C) + \sum_{w_f=1}^{NW_f} P_{w_f,t} - \sum_{j=1}^{NJ_b} D_{j,t} = \sum_{L=1}^{NL_b} PF_{L,t}
\]  

\[
PF_{L,t} = \frac{\delta_{j,t} - \delta_{j,t}'}{x_L}
\]  

\[
-PP_{L}^{max} \leq PF_{L,t} \leq PP_{L}^{max}
\]  

2.3. Gas System Constraints

The flow of gas through the gas pipelines with and without considering compressors can be formulated as (21)–(22) and (23), respectively. As is observable from these equations, the gas pipeline stream capacity will be improved using a compressor in the gas system. Equations (24) and (25) limit the gas pressure at each gas node and the gas load of suppliers, respectively. The minimum and maximum limits of the gas loads and the gas balance are denoted by (26) and (27), respectively [32].

\[
F_{pl,t} = sgn(\pi_{m,t}, \pi_{n,t}) C_{m,n} \sqrt{|\pi_{m,t}^2 - \pi_{n,t}^2|}
\]  

\[
sgn(\pi_{m,t}, \pi_{n,t}) = \begin{cases} 
1 & \pi_{m,t} \geq \pi_{n,t} \\
-1 & \pi_{m,t} \leq \pi_{n,t}
\end{cases}
\]  

\[
F_{pl,t} \geq sgn(\pi_{m,t}, \pi_{n,t}) C_{m,n} \sqrt{|\pi_{m,t}^2 - \pi_{n,t}^2|}
\]  

\[
\pi_{m}^{min} \leq \pi_{m,t} \leq \pi_{m}^{max}
\]  

\[
GW_{g}^{min} \leq GW_{g,t} \leq GW_{g}^{max}
\]  

\[
GL_{l}^{min} \leq GL_{l,t} \leq GL_{l}^{max}
\]  

\[
\sum_{g=1}^{NGW_m} GW_{g,t} + \sum_{g=1}^{NGS_m} (G_{out}^{g,t} - G_{in}^{g,t}) - \sum_{g=1}^{NGL_m} GL_{g,t} = \sum_{pl=1}^{NPW_m} F_{pl,t}
\]  

2.4. Thermal Storage Constraint

The studied multi-carrier energy system has considered thermal energy storage technology for investigating the possibility of storing thermal energy at some time intervals, and consuming it when required. The heat stored in the thermal energy storage can be formulated as (28) considering the thermal charge/discharge rates at each time and their associated efficiency, as well as the thermal losses of the storage and the latest level of thermal energy stored in the storage. The minimum and maximum capacities of the thermal energy storage system should be considered for the system (29). The rate of thermal energy charge and discharge should be limited to their maximum values as (30) and (31), respectively [33].

\[
B_{hs,t} = (1 - \eta_{hs}) B_{hs,t-1} + \eta_{ch} HS_{hs,t}^{ch} - \frac{HS_{dis}^{hs,t}}{\eta_{hs}} - \beta_{loss} SUL_{hs,t} + \beta_{gain} SDL_{hs,t}
\]  

\[
B_{hs,t}^{Min} \leq B_{hs,t} \leq B_{hs}^{Max}
\]  

\[
B_{hs,t} - B_{hs,t-1} \leq B_{hs}^{Max,charge}
\]
2.5. Systems Interconnection Constraints

The gas usage of each CHP is a function of the generated power and heat that can be stated as (32). Similarly, the gas usage of the power-only unit is associated with the electrical energy generated by the plant, which can be stated as (33). The value of the gas supply in providing plants’ fuel is a demand for the gas system (34). CHP, G1, and G2 are the demands of the gas system, as (35)–(36).

\[
F_{\text{CHP},i,t} = c_n + b_nP_{n,t} + a_n(P_{n,t})^2 + d_nH_{n,t} + e_n(H_{n,t})^2 + f_nH_{n,t}P_{n,t} + SUG_{n,t} + SDG_{n,t}, \quad n \in \mathbb{NC}
\]

\[
F_{G,i,t} = c_n + b_nP_{n,t} + a_n(P_{n,t})^2 + SUG_{n,t} + SDG_{n,t}, \quad n \in \mathbb{NG}
\]

\[
F_{e,t} = HR_eP_{e,t}
\]

\[
GL_{gl,t} = F_{\text{CHP},i,t}^G, \quad gl = i, \ldots, \mathbb{NC}
\]

\[
GL_{gl,t} = F_{G,i,t}^G, \quad gl = i, \ldots, \mathbb{NG}
\]

Water desalination is added to the studied system to provide water demand. Such a system interconnects the water carrier to the power network by using electrical energy to generate drinkable water. The power usage of the water stated desalination system can be formulated based on the water supply and efficiency as follows:

\[
P_{\text{desa},t} = Q_{\text{desa},t} \times \eta_{\text{desa}}
\]

The power usage of the in providing the water load of the network includes the power used by the desalination plant, water well pump, and water source pump, which can be represented by:

\[
P_{\text{water},t} = P_{\text{desa},t} + P_{\text{pu,wp},t} + P_{\text{pu,st},t}
\]

The water generated by the desalination system should satisfy the water demand of the whole system.

\[
WL_t = W_{\text{desa},t}
\]

3. Optimal Operation of the System Based on IGDT

3.1. Modeling of the Uncertainty

A fractional info-gap uncertainty modeling is performed as (40) for studying the uncertainty parameter in the multi-carrier energy networks, which is considered as the power load [34].

\[
U(\alpha, \overline{l_{m,h}}) = \left\{ l_{m,h} : \frac{l_{m,h} - \overline{l_{m,h}}}{\overline{l_{m,h}}} \leq \alpha \right\}, \quad \alpha \geq 0
\]

where \( l_{m,h} \) and \( \overline{l_{m,h}} \) are the real and predicted load, and the uncertain parameter is defined by \( \alpha \). The introduced scheme in (40) is an envelope-bound info-gap scheme, where the gap scale is in the proportion of the predicted amount.

3.2. Background of IGDT

In the energy networks, modeling the uncertainty of important input parameters is essential, concerning their variable characteristics such as demand. The IGDT approach is an effective tool for modeling the robustness and opportunity functions of the energy systems against variations in system parameters [34]. In this study, the authors have studied the uncertain nature of power load, which is defined by \( I \). Additionally, the decision variable is defined by \( q \).
The need for the optimal operation of the multi-carrier network describes the objectives anticipated from the network, which can be in cost function type or other forms. The evaluation of such requirements can be performed concerning robustness and opportunity functions as follows:

\[ \alpha = \max_{\alpha} \{ \alpha : \text{maximum total cost which is not higher than a specified cost} \} \]  \hspace{1cm} (41)

\[ \hat{\beta} = \min_{\beta} \{ \alpha : \text{minimum total cost which is less than a specified cost} \} \]  \hspace{1cm} (42)

The role of the robustness function is the evaluation of the robustness of the multi-carrier energy network against the probable increment of power demand and the immunity level of the network against the whole operation cost. In other words, the robustness function defines the maximum uncertainty value that the uncertain parameter can attain. Such a definition can be described as the risk-aversion capability of the IGDT. The robustness function can be formulated as [34]:

\[ \hat{\alpha}(C_r) = \max_{\alpha} \{ \alpha : \max(C(q, l)) \leq C_r \} \]  \hspace{1cm} (43)

where \( \hat{\alpha}(C_r) \) defines the resistance rate of the optimal energy management schedule against the uncertainty of the parameter. It is worth noting that the resistance of the decision for the system energy management can be increased by taking higher amounts of \( \hat{\alpha}(C_r) \).

The opportunity function measures the profit value, which can be attained from the uncertain nature of loads. Such a function describes the opportunity of receiving benefits from the desired deviation of uncertain parameters.

\[ \hat{\beta}(C_o) = \min_{\beta} \{ \alpha : \min(C(q, l)) \leq C_o \} \]  \hspace{1cm} (44)

3.3. Robustness Function

Robust decision-making for the operation of a multi-carrier network can be attained using the following problem:

\[ \hat{\alpha}(C_r) = \max_{\alpha} \{ \alpha : (\min_{l \in U(\hat{l}_m, h)} \text{cost}_\text{total}) \leq C_r = (1 + \omega)C_b \} \]  \hspace{1cm} (45)

where \( \hat{\alpha}(C_r) \) is the highest rate of uncertainty where the whole operation cost of the multi-carrier system cannot surpass a critical amount, \( C_r \). \( C_b \) is the lowest bound of the operation cost of the multi-carrier network that is predicted to pay, and the cost change factor for modeling the growth cost of the network is indicated by \( \omega \). For a risk-averse multi-carrier network, the robustness function of the presented IGDT scheme is maximizing the uncertain parameter whenever the needed operation cost is met.

\[ \hat{\alpha}(C_r) = \max \alpha \]  \hspace{1cm} (46)

\[ \left\{ \sum_{t=1}^{T} \left[ \sum_{n=1}^{NE} \left[ F(P_{n,t}) + SL_{n,t} + SD_{n,t} \right] + \sum_{g=1}^{NGW} \rho^{\text{gas}}GW_{g,t} + \sum_{g=1}^{NGS} C_s GS_{\text{out}}^{\text{gas}}_{g,t} \right] \right\} \leq C_r \]  \hspace{1cm} (47)

\[ l_{m,h} \geq (1 + \alpha)\bar{l}_{m,h} \]  \hspace{1cm} (48)

\[ l_{m,h} \leq (1 - \alpha)\bar{l}_{m,h} \]  \hspace{1cm} (49)

Concerning the uncertainty rate of \( \alpha \), the system operation cost will be in the upper bound if the greatest value of demand permitted by the IGDT is loaded at the uncertainty region \( \alpha \)—that is,
where the uncertain parameter variation on the objective function, can be simplified as:

\[
\hat{\alpha} = \max \alpha
\]

(50)

\[
\sum_{t=1}^{T} \sum_{m=1}^{NE} [F(P_{n,t}) + SU_{n,t} + SD_{n,t}] + \sum_{g=1}^{NGW} \rho^{gas} GW_{g,t} + \sum_{g=1}^{NGS} C_{gs} GS_{gs,t}^{out} \leq C_r
\]

(51)

\[
l_{m,h} = (1 + \alpha)\tilde{I}_{m,h}
\]

(52)

All the equality and inequality constraints of the system elements should be satisfied so that the uncertain parameter variation on the objective function, can be simplified as:

\[
\hat{\beta}(C_o) = \min \left\{ \alpha : \max_{\tilde{l}(a\tilde{I}_{m,h})} \text{cost}_{\text{total}} \leq C_o = (1 - \psi)C_b \right\}
\]

(53)

where \(\hat{\beta}(C_o)\) is the lowest rate of uncertainty where the total operation cost of the system cannot surpass a critical amount, \(C_r\), \(C_b\) is the lowest bound of the operation cost of the multi-carrier system predicted to pay, and the cost change factor for modeling the decreased cost of the network is indicated by \(\psi\).

For a risk-averse multi-carrier network, the robustness function of the presented IGDT is maximizing the uncertain parameter whenever the needed operation cost is met.

\[
\hat{\beta}(C_o) = \min \alpha
\]

(54)

\[
\sum_{t=1}^{T} \sum_{m=1}^{NE} [F(P_{n,t}) + SU_{n,t} + SD_{n,t}] + \sum_{g=1}^{NGW} \rho^{gas} GW_{g,t} + \sum_{g=1}^{NGS} C_{gs} GS_{gs,t}^{out} \leq C_o
\]

(55)

\[
l_{m,h} \leq (1 + \alpha)\tilde{I}_{m,h}
\]

(56)

\[
l_{m,h} \geq (1 - \alpha)\tilde{I}_{m,h}
\]

(57)

Concerning the uncertainty rate of \(\alpha\), the network operation cost will be minimum if the lowest value of demand permitted by the IGDT is demanded at the uncertainty zone, \(\alpha\), equal to \(l_{m,h} \leq (1 - \alpha)\tilde{I}_{m,h}\). Accordingly, the opportunity function, which considers the positive effect of the uncertain parameter variation on the objective function, can be simplified as:

\[
\hat{\beta}(C_o) = \min \alpha
\]

(58)

\[
\sum_{t=1}^{T} \sum_{m=1}^{NE} [F(P_{n,t}) + SU_{n,t} + SD_{n,t}] + \sum_{g=1}^{NGW} \rho^{gas} GW_{g,t} + \sum_{g=1}^{NGS} C_{gs} GS_{gs,t}^{out} \leq C_o
\]

(59)

\[
l_{m,h} = (1 - \alpha)\tilde{I}_{m,h}
\]

(60)
Similar to the robustness function, the optimal amount of the objective function will be obtained considering all the equality and inequality constraints of the system elements.

4. Case Study and Simulation Results

A multi-carrier system with gas, power, heat, and water carriers is selected for testing the proposed robust operation modeling of such systems based on the IGDT approach. The studied multi-carrier network, which is demonstrated in Figure 3, consists of a 6-bus electrical energy network, a 6-node natural gas network, a heat node, and a water node. Thermal energy storage technology is connected to the heat node and can store/release thermal energy based on the optimal operation strategy of the system. The data of the multi-carrier network consisting of the power, heating, gas, and water supply plants as well as the thermal energy storage technology are given from [33–36]. Table 2 consists of the characteristics of the thermal energy storage technology. The demands for the energy carriers, including electrical energy, heating, and water, are demonstrated in Figure 4. The price of gas in the simulation results is considered as 2 $/kcf.

![Figure 3. The studied multi-carrier energy network.](image)

Table 2. Characteristics of the thermal energy storage [35–38].

| **Data of the Thermal Energy Storage Technology** | **Data of the Thermal Energy Storage Technology** |
|-----------------------------------------------|-----------------------------------------------|
| $B_{Max}$ (MWh)                              | $B_{Min}$ (MWh)                               |
| $B_{Max,charge}$ (MWh)                        | $B_{Max,discharge}$ (MWh)                     |
| $B_{Min,charge}$ (MWh)                        | $B_{Min,discharge}$ (MWh)                     |
| $\eta_{hs}$                                   | $\eta_{hs,charge}$ $\eta_{hs,discharge}$     |
| 60                                            | 0                                             |
| 15                                            | 15                                            |
| 0                                             | 95%                                           |
| 90%                                           | 90%                                           |
Figure 3. The studied multi-carrier energy network.

Figure 4. The energy loads of the studied multi-carrier energy system.

4.1. The Analysis of Robustness Solution

A robustness analysis is performed based on the solution of the robustness function (39) and constraints (40)–(42), for which Figure 5 is provided. The robustness cost is the optimal value of the objective function considering the negative effect of the uncertain parameter variation on the objective function. The robustness function is provided as (50)–(52) and considers the negative effect of variation in the uncertain parameters on the objective function. Figure 5 demonstrates the relationship between robustness cost and robustness function. As can be observed in this figure, the operation cost of the multi-carrier network is increased by the increment of the robustness function. In other words, the multi-carrier system operator spends more money to attain a robust operation strategy for the system against the probable increment of the demand. The numerical results show that a $5000 greater cost for the system operation is effective in overcoming a 4% variation in the electrical energy demand. Additionally, by increasing the operation cost by $10,000, a 6% uncertainty in the electrical energy load can be handled by the presented robust model. It should be highlighted that the operation cost of the multi-carrier energy system increases with steps of $5000 in the robustness function.

Table 2. Characteristics of the thermal energy storage [35–38].

| Data of the thermal energy storage technology | Max, charge (MWth) | Min, charge (MWth) |
|---------------------------------------------|--------------------|--------------------|
| Max, discharge (MWth)                       | 15                 | 0                  |
| Min, discharge (MWth)                       | 15                 | 0                  |
| \(\eta\)                                 | 95%               | 90%               |

4.2. The Analysis of Opportunity Solution

The opportunity function is investigated considering the solution of the opportunity function (47) and constraints (48)–(50), for which Figure 6 is provided. The opportunity cost is the optimal amount of the objective function regarding the positive impact of the uncertain parameter variation on the objective function. The opportunity function is as (53)–(55), which is based on the positive influence of variation in the uncertain parameter on the objective function. Figure 6 demonstrates the relationship between the opportunity cost and opportunity function. The analysis shows that the operation cost of the multi-carrier energy system increases with steps of $5000 in the robustness function.

Figure 5. The relationship between operation cost and robustness function.
4.2. The Analysis of Opportunity Solution

The opportunity function is investigated considering the solution of the opportunity function (47) and constraints (48)–(50), for which Figure 6 is provided. The opportunity cost is the optimal amount of the objective function regarding the positive impact of the uncertain parameter variation on the objective function. The opportunity function is as (53)–(55), which is based on the positive influence of variation in the uncertain parameter on the objective function. Figure 6 demonstrates the relationship between the opportunity cost and opportunity function. The analysis shows that the operation cost of the multi-carrier network is decreased by the reduction in the robustness function. In other words, the whole network operator spends lower money to achieve a robust scheduling of the system. The numerical results report that the cost is reduced by $5000 for the system operator by a 3.9% decrease in the power load. Additionally, a reduction of $10,000 is attained for the operator by an 8.1% decrement of the power demand. It is worth noting that the operation cost of the multi-carrier energy system increases with steps of $2000 in the opportunity function.

![Figure 6](image-url)

Figure 6. The relation between the operation cost and the opportunity function.

4.3. IGDT-Based Robust Operation of the Multi-Carrier Network

This sub-section studies the IGDT-based operation of the multi-carrier system elements. The optimal generation scheduling of three power supply plants in three risk-seeker, risk-neutral, and risk-averse scenarios considering the uncertainty of electrical energy demand has been demonstrated in Figures 7–9. It can be seen from the reported results that the consideration of the risk-taker strategy results in producing less power, because the power load is reduced. Additionally, the consideration of the risk-averse strategy is effective in increasing the generation of electrical energy according to an increment in the electrical energy demand.
The optimal gas usage of the gas-fired power supply units CHP and G2 in three risk-seeker, risk-neutral, and risk-averse scenarios have been depicted in Figures 10 and 11, respectively. It is obvious that the risk-taker strategy is effective as less natural gas is consumed by both of the plants CHP and G2 since the power load is decreased. Additionally, the consideration of the risk-averse strategy results in growing the usage of natural gas considering the increase in the electrical energy demand of the whole system.

![Figure 7. The power production schedule of the CHP plant.](image)

![Figure 8. The power production schedule of the gas-fired G1 plant.](image)

![Figure 9. The power production schedule of the non-gas-fueled G2 plant.](image)
The optimal gas usage of the gas-fired power supply units CHP and G2 in three risk-seeker, risk-neutral, and risk-averse scenarios have been depicted in Figures 10 and 11, respectively. It is obvious that the risk-taker strategy is effective as less natural gas is consumed by both of the plants CHP and G2 since the power load is decreased. Additionally, the consideration of the risk-averse strategy results in growing the usage of natural gas considering the increase in the electrical energy demand of the whole system.

**Figure 10.** The gas consumption of the CHP plant.

**Figure 11.** The gas usage of the gas-fueled plant, G2.
The CHP plant supplies the total heat demand of the system, which has an interdependency with the power supply of the plant. The heat generation of the CHP unit during the 24-h scheduling time horizon is shown in Figure 12, which shows that the heat supply of the plant is more than the heat load that is shown in Figure 4 at the time interval from $t = 5$ h to $t = 8$ h and when the heat supply is less than the heat load at a time duration from $t = 9$ h to $t = 12$ h, which highlights the role of the thermal energy storage system. The heat charge/discharge of the thermal energy storage technology as well as the scheduling for thermal energy stored in this storage is depicted in Figure 13 based on (26)–(29), which helps the system to store excess heat at off-peak time intervals and discharge it at on-peak time intervals. The optimal set points of the thermal energy storage are selected using the optimization solver to minimize the operation cost of the system.

Figure 12. The heat generation of the CHP plant.

Figure 13. The schedule of thermal storage.
The power consumption of the water desalination system to satisfy the shown water demand is obtained as shown in Figure 14, which is based on (31) and (32). The desalination plant has consumed a total electrical energy of 405.17 MW from bus 5 of the power system within the 24-h scheduled time interval. The power supply of the wind turbine during the studied time horizon is shown in Figure 15, which is injected to bus 5 of the power network. The total power supply of the wind turbines installed in the system is attained as 713.92 MW.

![Figure 14. The power usage of the water desalination unit.](image)

![Figure 15. The power production of the wind turbines.](image)
5. Conclusions

This study presented an IGDT-based robust operation of multi-carrier energy networks with power, gas, heating, and water carriers considering the thermal energy storage system. In the proposed model, the network operator is responsible for managing an uncertain electrical energy load and analyzing the role of load variation in the optimal operation strategy of the whole energy system. Accordingly, the robustness and opportunity functions for the multi-carrier network based on the IGDT method are presented to be used by the system operator in making proper decisions on the system operation, considering the electrical energy load. The results for the multi-carrier energy system elements are reported for three scenarios, including risk-neutral, risk-averse, and risk-taker according to positive, negative, and neutral aspects of the uncertain parameter. Considering the risk-averse strategy, the multi-carrier energy system operator decides to pay more money for generating sufficient electrical energy to be more robust against power demand uncertainty. On the other hand, considering the risk-taker strategy, the operator attains benefits within the probable decrement of power demand according to the dependency of the operation cost of the multi-carrier network on the whole used power. The role of the thermal energy storage system in the operation of the multi-carrier energy system was also analyzed by reporting the heat charge/discharge of the thermal energy storage technology as well as the scheduling for thermal energy stored, which verified the optimal scheduling of the thermal energy storage in managing the heat load of the system. Future works will be focused on the investigation of new demand, consisting of an air-conditioning and battery system with the penetration of solar cells as well as considering the uncertainty associated with weather prediction [39]. Additionally, resilience is of great importance in the operation of a multi-carrier energy system and can be concentrated on in a future study.

Author Contributions: Conceptualization, M.N.-H.; methodology, M.N.-H.; software, M.N.-H.; validation, M.N.-H., B.M.-I., S.A.; formal analysis, B.M.-I., S.A.; investigation, M.N.-H., B.M.-I., S.A.; resources, M.N.-H., B.M.-I., S.A.; data curation, M.N.-H.; writing—original draft preparation, M.N.-H.; writing—review and editing, B.M.-I., S.A.; visualization, M.N.-H.; supervision, B.M.-I., S.A.; project administration, M.N.-H.; supervision, B.M.-I., S.A.; funding acquisition, M.N.-H.; supervision, B.M.-I., S.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by Iran National Science Foundation (INSF) under grant No. 97016932.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

| Table A1. Nomenclature. |
|-------------------------|
| **T**                   | Total time duration |
| **NE**                  | Number of power plants |
| **NGW**                 | Number of gas suppliers |
| **t**                   | Time interval |
| **n**                   | Power plant |
| **SU_{n,t}/SD_{n,t}**   | Start-up/shut-down cost of the non-gas-fueled power unit at each time interval |
| **su_{n}/sd_{n}**       | Start-up/shut-down price of non-gas- fueled power unit |
| **SUG_{n,t}/SDG_{n,t}** | Start-up/shut-down gas consumption of gas-fired power plant at each time interval |
| **su_{g,n}/sd_{g,n}**   | Start-up/shut-down gas usage rate of gas-fueled power unit |
| **P_{n,t}**             | The power supply of plant |
| **F**                   | The operation cost of plants |
| **O**                   | Objective function |
Table A1. Cont.

| Symbol | Description |
|--------|-------------|
| $p_{\text{min}}^n/p_{\text{max}}^n_n$ | Min/max power limit of plants |
| $R_{\text{up}}^n/R_{\text{down}}^n_n$ | Ramp up/down of generation units |
| $h_{\text{on/off}}$ | On/off status of power plant |
| $p_{\text{wind}}^t$ | The power output of the wind turbine |
| $D_{\text{it}}$ | Electrical energy load of the system |
| $PF_{\text{it}}$ | Power flow through the system lines |
| $\delta_{\text{bus}}$ | Voltage angle of the bus of the electrical energy system |
| $x_{\text{i}}$ | Power system line reactance |
| $p_{\text{max}}^\text{transmission}^L$ | Power transmission capacity of the power system line |
| $F_{\text{gas}}^t$ | Gas transmission through the gas pipeline |
| $G_{\text{system pressure}}^n$ | The gas pressure of the gas system node |
| $W_{\text{wind}}^\text{max/n}$ | Min/max gas pressure of gas system node |
| $GW_{\text{in}}^t$ | Supplied gas by the gas supplier |
| $GL_{\text{gas load}}^t$ | Gas load |
| $GW_{\text{in}}^\text{min/max}/GW_{\text{in}}^\text{max}$ | Min/max gas supply |
| $GL_{\text{gas load}}^\text{min/max}/GL_{\text{gas load}}^\text{max}$ | Min/max gas load |
| $\alpha, \beta, \gamma, \delta, \epsilon, \zeta, \eta, \theta, \phi, \xi, \pi, \rho, \sigma, \tau, \upsilon, \phi, \chi, \psi, \omega, \Omega$ | Gas consumption/operation cost coefficients of the power unit |
| $P_{\text{water}}^t$ | Power usage of the water carrier |
| $P_{\text{desal}}^t$ | Power usage of the desalination system |
| $P_{\text{wp}}^t$ | Power usage of the water well pump |
| $P_{\text{ws}}^t$ | Power usage of the water source pump |
| $B_{\text{thermal level}}$ | The thermal energy level of the thermal storage system |
| $H_{\text{charge}}^\text{thermal storage system}$ | Thermal energy charge of the thermal storage system |
| $H_{\text{discharge}}^\text{thermal storage system}$ | Thermal energy discharge of the thermal storage system |
| $\eta_{\text{charging}}^\text{thermal storage system}$ | Thermal energy charging efficiency of the thermal storage system |
| $\eta_{\text{discharging}}^\text{thermal storage system}$ | Thermal energy discharging efficiency of the thermal storage system |
| $\eta_{\text{thermal storage system}}$ | Thermal storage efficiency |
| $B_{\text{min/Max}}^\text{thermal storage system}$ | Min/max heat storage capacity of the thermal storage system |
| $B_{\text{Max,change/discharge}}^\text{thermal storage system}$ | Maximum charge/discharge rate of the thermal storage system |
| $WL_{\text{water load}}$ | Water load at each time |
| $W_{\text{desal}}^t$ | Water generation of the desalination system |
| $C_{(q,t)}$ | System model |
| $l$ | Uncertain nature of energy loads |
| $q$ | Decision variable |
| $\lambda(C_r)$ | Resistance rate of the optimal energy management schedule |
| $\beta$ | Minimum amount of $\alpha$ |
| $I_{\text{real/predicted load}}$ | Real and predicted load |
| $C_r$ | Critical amount |
| $C_0$ | Lowest bound of the operation cost |
| $\alpha$ | Uncertainty rate |
| $\beta(C_0)$ | The lowest rate of uncertainty that network operation cost cannot surpass a critical amount $C_r$ |
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