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Modeling a Cooperation Environment for Flexibility Enhancement in Smart Multi-Energy Industrial Systems

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Orientador: Prof. Dr. João Paulo da Silva Catalão
Co-orientador: Prof. Dr. João Carlos de Oliveira Matias

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Resumo

Aspetos ambientais têm merecido destaque na conceção dos sistemas de energia do futuro, onde o desenvolvimento sustentável desempenha um papel fundamental. O desenvolvimento sustentável no sector da energia tem sido definido como uma potencial solução para a melhoria do sistema energético, como um todo, para atender às exigências energéticas do futuro, sem interferir com o ambiente ou com o fornecimento de energia. A este respeito, o tema principal desta tese corresponde ao estudo do impacte transversal e multidisciplinar de vários vetores energéticos (eletricidade, gás, etc.) na operacionalidade e flexibilidade do sistema. A coordenação de vários vetores energéticos sob o conceito de um sistema de multi-energia (MES) introduz novas fontes de flexibilidade operacional para os gestores do sistema. Um MES considera as interações entre os portadores de energia e os agentes de decisão num ambiente interdependente com vista a aumentar a eficiência global do sistema e a revelar as sinergias subjacentes entre esses portadores de energia. Esta tese propõe uma metodologia para modelar agentes multi-energia (MEP) que são aglomerados com base no sinal de preço no MES em ambiente competitivo. Um MEP pode usufruir ou disponibilizar um ou mais vetores energéticos. Numa etapa inicial, a evolução do sistema de energia tendo por base uma arquitetura independente, hoje em dia, para uma integração total ao nível do MES é estudada, e a estrutura proposta do tipo fractal é descrita. Posteriormente, o comportamento operacional associado a parques de estacionamento com estação de carregamento para veículos elétricos do tipo plug-in, bem como a dependência externa da demanda multi-energia, são modelados numa arquitetura tipo MES para incrementar a flexibilidade operacional dos sistemas de energia locais (LES). Nesse ambiente do tipo fractal, podem existir conflitos ao nível da tomada de decisão entre MEPs pertencentes a diferentes camadas. A flexibilidade inerente ao MES é o fator principal para modelar esses conflitos com base numa estrutura multicamada. O conflito entre duas camadas de agentes é modelado recorrendo a uma abordagem bi-nível. Neste problema, o primeiro nível corresponde ao nível MEP, onde cada agente visa maximizar o seu lucro satisfazendo os intercâmbios de energia ao nível do LES. O preço desses intercâmbios de energia ao nível do LES corresponde ao resultado final para esse nível. No nível mais baixo, os LESs otimizam o seu balanço energético, tendo por base o sinal do preço resultante do nível superior. O problema é transformado num problema de programação matemática com restrições de equilíbrio (MPEC) por meio da teoria da dualidade. Na próxima etapa, é modelada uma elevada penetração de MEPs no mercado da eletricidade, determinando o impacte no equilíbrio de mercado. Nesse modelo, um MEP pode participar nos mercados de energia a nível local e global, simultaneamente. Os potenciais conflitos entre um MEP e os outros agentes de mercado são também modelados recorrendo à programação bi-nível. Os problemas bi-nível são posteriormente transformados em problemas mono-nível com recurso à programação linear inteira-mista, aplicando também a teoria da dualidade.

Palavras-chave

Modelação da dependência, Avaliação da flexibilidade, Sistema de energia do futuro, sistema de multi-energia, veículos elétricos do tipo plug-in

Abstract

Environmental aspects have been highlighted in architecting future energy systems where sustainable development plays a key role. Sustainable development in the energy sector has been defined as a potential solution for enhancing the energy system to meet the future energy requirements without interfering with the environment and energy provision. In this regard, studying the cross-impact of various energy vectors and releasing their inherent operational flexibility is main topic.

The coordination of various energy vectors under the concept of multi-energy system (MES) has introduced new sources of operational flexibility to the system managers. MES considers both interactions among the energy carriers and the decision makers in an interdependent environment to increase the total efficiency of the system and reveal the hidden synergy among energy carriers.

This thesis addresses a framework for modeling multi-energy players (MEP) that are coupled based on price signal in multi-energy system (MES) in a competitive environment. MEP is defined as an energy player who can consume or deliver more than one type of energy carriers. At first, the course of evolution for the energy system from today independent energy systems to a fully integrated MES is presented and the fractal structure is described for of MES architecture. Moreover, the operational behavior of plug-in electric vehicles' parking lots and multi-energy demands' external dependency are modeled in MES framework to enhance the operational flexibility of local energy systems (LES).

In the fractal environment, there exist conflicts among MEPs' decision making in a same layer and other layers. Realizing the inherent flexibility of MES is the main key for modeling the conflicts in this multi-layer structure. The conflict between two layers of players is modeled based on a bi-level approach. In this problem, the first level is the MEP level where the player maximizes its profit while satisfying LES energy exchange. The LES's exchange energy price is the output of this level. In the lower level, the LESs schedule their energy balance, based on the upper level input price signal. The problem is transformed into a mathematical program with equilibrium constraint (MPEC) through duality theory.

In the next step, high penetration of multi-energy players in the electricity market is modeled and their impacts on electricity market equilibrium are investigated. In such a model, MEP participates in the local energy and wholesale electricity markets simultaneously. MEP and the other players' objectives in these two markets conflict with each other. Each of these conflicts is modeled based on bi-level programming. The bi-level problems are transformed into a single level mixed-integer linear problem by applying duality theory.

Keywords

Dependency modeling, flexibility assessment, future energy system, multi-energy system (MES), plug-in electric vehicle.

Contents

List of Figures

List of Tables

List of Acronyms

AB	Auxiliary boiler
CBDR	Carrier-based demand response
CHP	Combined heat and power
CS	Carrier share
DER	Distributed energy resource
DR	Demand response
ED	External dependency
EC	Energy converter
ES	Energy storage
FESR	Fuel energy saving ratio
Genco	Generation company
HS	Heat storage
IL	Interruptible load
ISO	Independent system operator
KKT	Karush-Kuhn-Tucker
LES	Local energy system
LRUF	Local resource utilization factor
MEP	Multi-energy player
MED	Multi-energy demand
MES	Multi-energy system
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MPEC	Mathematical programming with equilibrium constraints
PEV	Plug-in electric vehicle
PL	Parking Lot
PV	Photovoltaic array
RER	Renewable energy resource
Retailer	Retailer company
TOU	Time of use tariff
Wind	Wind generation

Nomenclature

Subscripts

e	Electricity
g	Natural gas
h	Heat
i	Number of LES
j	Number of retailer
k	Number of Genco
r	Reserve
t	Time interval
ω	Scenario

Superscripts

AB	Auxiliary boiler
Agg	Aggregator
ar	Arrived PEVs in PL
Bid	Bidding of electricity producers
CHP	Combined heat and power
cha	Heat/electric storage charging
$dcha$	Heat/electric storage discharging
dep	Departed PEVs from PL
$down$	PEVs' departure SOC is less than Scenario
Du	Dual problem
E	Equality constraints
ES	Electric storage
EM	Energy market
EV	Electric vehicle
$Forecast$	Forecasted amount of RER
$Genco$	Generation company
$G2V$	Grid to Vehicle
HS	Heat storage
in	Input energy to MEP, HS or ES

LES	Local energy system
MEP	Multi-energy player
MED	Multi-energy demand
N	Non-equality constraints
new	New matrix or vector
old	Old matrix or vector
$Offer$	Offering of electricity consumers
out	Output energy from MEP, HS, or ES
PL	Parking lot
Pr	Primal problem
PV	Photovoltaic array
$Retailer$	Retailer company
Sc	Scenario
up	PEVs' departure SOC is more than Scenario
$V2G$	Vehicle to Grid
$Wind$	Wind generation

Parameters and Variables

Ca	Total capacity of PEVs in PL
Cd	Cost of battery degradation.
FOR	Forced outage rate.
$g,\ G$	Amount of natural gas supply
M	A large enough positive constant for the relaxation of primal and dual constraints.
N	Number of PEVs in PL.
$p,\ P$	Amount of electricity generation
$q,\ Q$	Amount of heat production
$r,\ R$	Amount of Reserve
$soc,\ SOC$	State of charge
T	Time period
u	Binary variable
v	Decision variable
$w,\ W$	Electricity

λ	Dual variables for equality constraints
$\underline{\mu}, \overline{\mu}$	Dual variables for the lower and upper limits of non-equality constraints.
ξ	Dual variables for equality constraints in specific time intervals.
γ	Charge/discharge rate
η	Efficiency
π, Π	Energy price
κ	Shadow price for energy balance equation of electricity market.
ρ	Scenario probability.
$\mathbf{E}$	Vector of equality constraints.
$\mathbf{I}$	Matrix of convertors participation in reserve.
$\mathbf{N}$	Vector of non-equality constraints.
$\mathbf{T}$	Vector of equality constraints in specific time.
$\mathbf{X}$	Vector of decision variables for dual problems.

Remark 1: An underlined (overlined) variable is used to represent the minimum (maximum) value of that variable.

Remark 2: Capital letters denote parameters and small ones denote variables.

Chapter 1

An Introduction to the Research Main Problems and Solving Procedure

1.1 Research Motivation

Environmental aspects have been highlighted in architecting future energy systems where sustainable development plays a key role. Sustainable development in the energy sector has been defined as a potential solution for enhancing the energy system to meet the future energy requirements without interfering with the environment and energy provision. In this context, emerging technologies and change in the business paradigm of the energy sector have introduced new challenges and opportunities to energy system managers supplying future energy needs. The development of distributed energy resource (DER) technologies, e.g., energy converters and storage, has increased the dependency of energy carriers. On the other hand, establishment of new business environments and the participation of more players in the energy system's decision-making process have increased the dependency of stakeholders' decision variables.

In order to address these issues, the concept of multi-energy systems (MES) has been introduced in energy system. The MES concept regards the integration of various energy carriers (e.g., electricity, natural gas, district heating, etc.) and their operation from technical and economical points of view to enable energy and information interaction in different levels.

With the development of MES in larger scales, their studies have been conducted with two perspectives. In the first perspective, each energy infrastructure is studied, independently and the impact of other energy carriers are considered as constant or variable inputs to its studies. Based on this method, multi-level planning studies have been introduced that infrastructure were prioritized in this framework based on their importance and planning dynamics.

But due to fundamental changes in the role of demand side players in decision making framework of energy system, independent models are not suitable anymore for the studies of MES and their challenges. These changes include:

- Diversification of energy infrastructures and their expansion;
- Introducing new energy converters in supply side and more interdependency of energy infrastructures, which makes their security and economy issues more dependent;
- Changes in the attitude of demand to benefit new prospects. In this situation customers prefer to achieve a certain energy service from various energy pathways.

The last item might be the most important one. Although achieving diversification of energy sources and carries is primary motivation for dependent studies of energy carriers, the operational flexibility of demand side players to substitute their energy consumption between energy carriers has brought great opportunities for the management and integrated planning of energy carriers. In fact, in the current situation, manager and decision makers are persuaded to multi-infrastructure development by the demand inherent flexibility. Hence, the first step to utilize such capabilities is the modeling of MES and defining the role of energy player in this context.
Therefore, the second perspective focuses on this target, which is proper deliver of energy services to the end users, beyond the type of energy carrier or energy pathway from primary energy resources. In the modeling of this perspective, all infrastructures should be modeled as an integrated system, and their mutual impacts should be studied, simultaneously. This new environment needs new players to utilize the inherent flexibility of the system and link energy carriers markets. The following question should be answered by decision makers in this situation:

- What is the characteristics of this new players who can trade in various energy markets, simultaneously?
- How is the cooperation environment for these players and what is the equilibrium point for their operational strategies?

- In larger scales, and after high penetration rate of these players in energy system, what is the impact of their strategies on the energy wholesale markets equilibrium?

In order to answer the aforementioned questions, researchers have presented a platform for modeling of mutual effects of energy carriers. The proposed platform demonstrates energy system as a set of operation centers as energy modules connected by energy interconnectors. The proposed model was able to address many issues ahead of the decision makers in the new environment. Furthermore, the attitude and behavior of energy player in different energy carriers and their optimum energy interactions were properly modeled. This new models alters passive energy players into active players that can interact energy with other energy players in different levels. The presence of various multi energy players in a limited geographical area causes their energy and financial interaction to change from a single carrier approach to multi-energy carrier interactions. These interactions introduce new opportunities ahead of multi-energy players, to aggregate an operational flexibility of lower levels' energy players to impact on energy wholesale market parameters.
Hence, studying the cooperation environments of these energy players promises new local energy interactions and contributes to filling the gap between energy wholesale markets and end users. On the other hand, studying strategic behavior of multi energy players determines the long-term equilibrium of energy system beyond short-term behavioral fluctuations. It is essential to determine the influence of these multi-energy players, which are the missing link in the chain of energy markets and consumer, on wholesale markets, which tend to determine the short term prices and long term trends.

1.2 Research Background

In the literature, MES is defined as energy systems with more than one energy carrier [1]. MES is divided into two main parts, namely, operation centers and interconnectors. Operation centers represent the integration of energy resources (e.g., energy converters and storage) and interconnectors are the energy transmitters between operation centers, such as gas pipelines and power lines. Surveys on MES are concentrated on two areas. In the first area, the management of a single operation center is investigated and new models are developed for integrating new energy elements, uncertain resources, and decision-making frameworks in various time domains. In [2] and [3], optimal operation frameworks for residential and industrial energy hubs are designed, respectively.

The integration of renewable energy resources (RER), demand response (DR) programs, plug-in electric vehicles (PEV) and storage is considered in [4, 5, 6, 7], respectively. Moreover, [8] and [9] evaluate the energy hub approach's proficiency in the long run.

In the second area, a set of operation centers and their corresponding interconnectors are considered in an interactive environment and the developed models are investigated from economic, technical, and environmental aspects. In [10], an optimal energy scheduling and energy interaction for a set of operation centers is proposed. The model is extended in [11] and an evolutionary method is implemented to increase the accuracy of results and the speed of convergence. Furthermore, in [12], a decentralized control model is proposed for a set of energy hubs to coordinate their operation.

Although many studies have been oriented to model the MES environment, the aggregation of demand side energy resources under the concept of MEP to participate in electricity wholesale market have not been addressed yet. The aggregation of a set of energy carriers introduce more flexibility to MEP for participation in electricity market. Moreover, using interactive models instead of centralized or tariff based models for aggregation of demand side energy resources, increase the level of operational flexibility and the utilization of local energy resources in demand side.

1.3 Thesis Objectives and Contributions

The very first step in studying the interactions between multi energy players is to determine the future perspective of energy system. In this vision, the impact of high penetration rate of new energy players on MES in different evolution steps should be considered. In the next step, a cooperation environment should be devised for energy players considering their inherent characteristics to interact with other energy players. This interactive environment guarantees the active participation of multi-energy players, and motivates these players to enhance the total flexibility of the system in long-term. Behavioral analysis of energy players in the proposed environment creates a better background for decision makers towards the development incentives and future needs of energy systems .

Another important objective of this thesis is to model the impact of energy players and demand side cooperation environments on the equilibrium point of energy wholesale market. Development of local energy markets is expected in the near future, which can be implemented with suitable mechanisms. On the contrary, aggregation of present energy markets under the concept of integrated energy market needs complex mechanism that is not achievable in near future. Therefore, it is expected that in the course of evolution for energy systems, local energy markets besides independent energy wholesale markets be achievable. Thus, studying the mutual impact of these markets and local energy interactions on energy wholesale markets is considered as one of the objectives in this thesis.

Based on the determined objectives the contribution of this thesis are as follow:

- For demand side modules modeling:
  - Modeling PEVs' PL in MES considering the uncertain behavior of PEV owners, which can be operated in both V2G and G2V modes;
  - Modifying the mathematical model of energy hub to consider the reserve ancillary service in MES;
  - Developing a new operational model of PL to consider its interface with MES and PEVs simultaneously.
  - Represent customer's choice in the MES model to increase flexibility, by extending the matrix model of the MES to incorporate the effects of dependent demand;
  - Extend the degrees of freedom for applying DR by proposing a CBDR program;
  - Assess the stochastic behavior of the demand side for selecting the carriers by means of implementing scenarios incorporating CBDR programs.

- For local cooperation environment framework:
  - Proposing an aggregation approach for MEP in distribution level that couples LES based on an equilibrium energy price signal;
  - Modeling the proposed framework based on the bi-level approach;
  - Introducing two novel indices to assess the flexibility of different regulatory frameworks in distribution level;
- For impact high penetration of MEP on energy wholesale market parameters.
  - Modeling the strategic behavior of an MEP in electricity wholesale market within a bi-level decision making problem;
  - Considering the MEP as a medium to participate the demand side resources in the market in an aggregated manner for electricity, gas, and heat energy carriers and model its behavior through a bi-level decision making problem;
  - Evaluating the impact of a high penetration of MEP on the equilibrium points of electricity wholesale market and the local aggregation of demand side energy resources and the cross impact of these two sets of equilibrium points.

1.4 Modeling Procedure

This thesis addresses a framework for the aggregation of demand side energy resources under the concept of MEP to participate in electricity wholesale market. At first, the course of evolution for the energy system from today independent energy systems to a fully integrated MES is presented and the fractal structure is described for MES architecture. The proposed fractal structure consists of four layers, namely, energy market, MEP, local energy system (LES), and multi-energy demand (MED). The multi-layer structure represents the behavior and scale of each energy player in the proposed MES. A short description of each layer follows:

- The energy market consists of individual energy carrier markets linked by MEPs.

- MEP is an energy aggregator who interacts with a set of LES and participates in energy markets.
- LES is a local energy network equipped with demand side energy resources delivering required energy services to MED.
- MED is the lowest level in this multi-layer structure and can be a set of end-users consuming various energy carriers.

Emerging MEP in this environment changes business paradigm in MES. MEP can exchange energy in various forms and prefer to trade energy packages (consisting of more than one form of energy) to mitigate their risk and enhance their security of supply. In this condition, new energy markets will be encouraged to be established that enable trading various energy packages among MEPs. Expansion of multi-energy markets will motivate MEPs to enhance their flexibility and their share in those markets. Furthermore, some players can also participate in more than one multi-energy market to exploit more benefit from arbitrage among markets.

An increase of these activities will make multi-energy markets more dependent. This dependency initiates the integration of these markets from organizational and technical or only financial points of view. The vision for this environment is a fully competitive integrated energy system that provides highly secure and cheap energy services for all users based on their requirements regardless of the energy carrier type. After architecting the fractal structure the next step is modeling the component and decision making problem of energy players from lower to upper layers.

In this regard, in MED layer, the concept of internal and external dependencies are proposed to model the dependency of MED in LES operation study. Internal dependencies refer to possible changes in the energy source in the presence of energy converters and storage, and are managed by the system operator through the control strategies applied to the equipment. External dependencies (EDs) are due to the choice of the energy supply according to customer preferences when alternative solutions are available. EDs are addressed through a stochastic model in order to take into account the possible uncertainty in the customers' decisions. This model is then used to introduce carrier-based demand response (DR) in which the user participates in DR programs aimed at promoting the shifting among different energy sources by preserving the service provided to the end users. Moreover, besides modeling the conventional energy storages and converters in LES, the integration of plug-in electric vehicles in the electric parking lots as emerging components in future energy system is modeled in LES layer. As a result of the PL operational characteristics, its behavior in both energy and reserve markets is considered. The energy hub model is modified to handle the participation of MES elements in the reserve market. Moreover, a stochastic approach is applied to model the uncertainty of the behavior of PEVs' owners in PL.

In such an environment, MEP is defined as an aggregate who exchanges energy with LESs and participate in electricity market. There exist conflicts among MEP and LESs decision making. Realizing the inherent flexibility of MES is the main key for modeling the conflicts in this multi-layer structure. The conflict between these two layers of players is modeled based on a bi-level approach. In this problem, the upper level is the MEP level where the operator maximizes its profit while satisfying LES energy exchange. The LES's exchange energy price is the output of this level. In the lower level, the LESs schedule their energy balance, based on the upper level input price signal. The problem is transformed into a mathematical program with equilibrium constraint (MPEC) through duality theory.

In the last step, high penetration of MEPs in the electricity market is modeled and their impacts on electricity market equilibrium are investigated. In such a model, MEP aggregates LESs and participates in the wholesale electricity markets, simultaneously. MEP and the other players' objectives in these two layers conflict with each other. These conflicts is modeled based on bi-level programming. The bi-level problems are transformed into a single level mixed-integer linear problem by applying duality theory.

Numerical results showed that the local energy price equilibrium is related to the local energy resources of LES. Due to the mutual dependency of the energy carriers, LES may have variable marginal costs for the energy production in the operation period. This time-based marginal cost affects local market parameters and, if the penetration rates of MEP increase, it can affect them. Therefore, after increasing the penetration rate of MEPs, numerical results showed the mutual effects of the local energy market and the electricity market. Figure 1.1 depicts the summary of solving procedure of thesis main research problem.

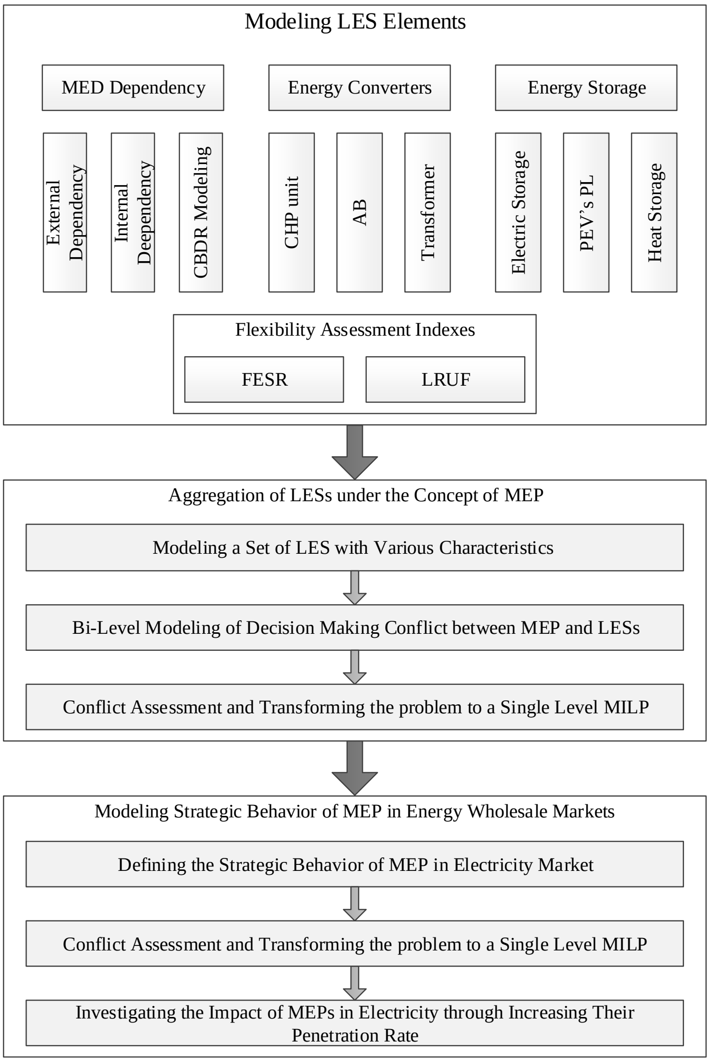

Figure 1.1: Schematic of research problem and solving procedure.

1.5 Thesis Organization

The writing of the thesis involves the following foreseen chapters:

Chapter 1: As it is shown in the first chapter the main research questions are presented. Moreover, beside defining the contribution of the thesis modeling procedure to aim the thesis goal is explained.

Chapter 2: In this chapter in the first step the research background for MES is surveyed and after that the perspective of future energy system is depicted. Moreover, in this chapter, a fractal structure for MES is proposed that helps to define the role of each energy player in the future energy system perspective.

Chapter 3: The plug-in electric vehicles aggregation under the concept of urban parking lots in the MES framework is considered in this chapter. The PEVs' PL is assumed as a storage with intermittent nature that can enhance the flexibility of local energy system. The uncertain behavior of PEV's owners is modeled based on stochastic programming approach in this part.

Chapter 4: This chapter is dedicated to define the external and internal dependency in MES. The new concept of carrier-based demand response is modeled in this part to increase total flexibility of local energy systems in the presence of high penetration of distributed energy resources.

Chapter 5: This chapter addresses a framework for modeling multi-energy players (MEP) that are coupled based on price signal in MES. The MEP is defined as an economical player that aggregates LES and participates in wholesale energy markets. The decision making conflict between MEP and LESs is model based on bi-level approach. The bi-level optimization problem is transformed to a mathematical programming with equilibrium constraints (MPEC) and solved by GAMS package.

Chapter 6: In this Chapter, at first the behavior of a typical MEP is modeled in electricity market. After that the share of MEP in electricity market is increased to survey its impact on electricity market interactions. The decision-making conflict of MEP with other energy players for aggregation of LES and participation in electricity market is modeled based on a bi-level approach

Chapter 7: The research main outlines a concluding remarks are presented in this chapter.

Chapter 2

Literature Review and Future Trends in the Research Area of Multi-Energy System

2.1 Introduction

In this chapter, a review of studies in the field of Multi-energy system (MES) has been presented. In this regard, the references related to MES are the first to be reviewed. Then Course of evolution for MES from today's energy system to fully integrated MES are next investigated.

2.2 Multi-energy system

Energy carriers include electricity and heat as well as solid, liquid and gaseous fuels. They occupy intermediate steps in the energy-supply chain between primary sources and end-use applications. An energy carrier is thus a transmitter of energy. For reasons of both convenience and economy, energy carriers have shown a continual shift from solids to liquids and more recently from liquids to gases, a trend that is expected to continue. At present, about one third of final energy carriers reach consumers through distribution grids in the form of electricity and gas. The share of all grid-oriented energy carriers could increase to about one half of all consumer energy by 2100. A system of energy carriers that includes more than one energy carriers is called multi-energy system (MES) [13]. Figure 2.1 illustrates the role of energy carriers in the context of supply chain for energy systems from energy sources to end-users.

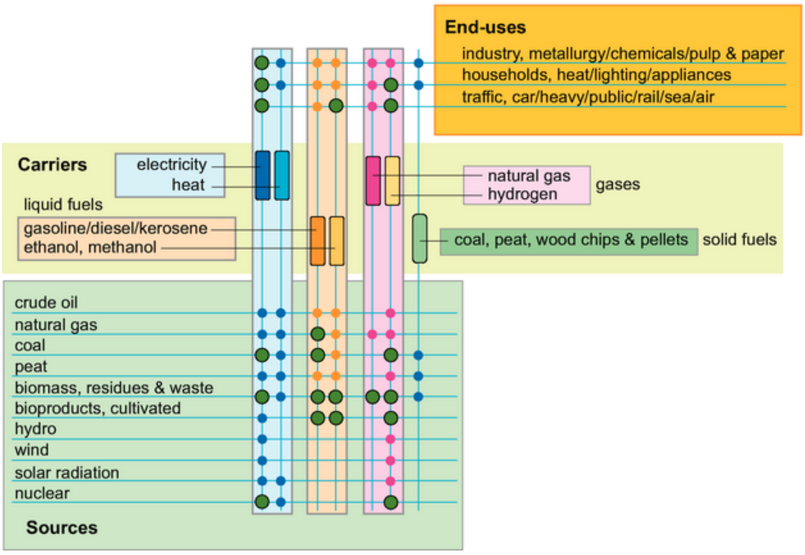

Figure 2.1: Supply chain of energy system from primary resources to end-user.

2.3 Early stage models for dependent energy carriers

Increasing the number of energy converters has made energy networks more dependent to each other, while they were previously separated, and produce, transmit, and deliver energy in different layers, independently. Hence, studying the effects of other energy carriers on one energy carrier in the new environment gained more attention. Nonetheless, these interdependencies were mostly uni-direction in energy system. In other words, two energy carriers may have utilized a single source of energy, or an energy carrier might have been the primary resource for another carrier. Such dependencies made energy networks more of an open loop system, in which an energy crossed a defined line downward to the consumer and it might have gotten different forms along the path. This intrinsic could easily model the mutual effects of various energy infrastructures. In this regard, early stage studies tended to investigate energy infrastructures separately, and the effects of other infrastructure was added as variable or constant input. In this way, the research model was studied solely based on these inputs, and managers of energy systems were thus not concerned the optimization of input.

With further development of models and increased dependency of energy infrastructures, multi-level programming was designed for centralized studies of MES, and infrastructures were considered based on their priority and development dynamics.

In this method, the output of every level of programming was used as input for the next level.
In this regard, the grid-bounded nature of natural gas energy carriers and its geographical extension along power system has made these two carriers undisputed elements of MES. Development of new gas convertor has further intensified the importance of gas energy carrier as a primary resource for power plants. The following are among the effects of gas network on power systems [14]

- the price of gas network directly affects the economic distribution of production, planning of unit's cooperation, and production costs. The increases of gas price as a results of atmospheric incidents or effects may lead to increased price of power production of gas-based plants, and consequently, lower shares of energy production by such plants.
- Pressure drop in gas pipelines may lead to the loss of gas-based power plants. In such cases, units can rely on natural gas reservoirs in the network or utilizing alternative fuels, albeit with lower levels of production.
- In the bad weather climates, the simultaneous demand for gas and electric may lead to spike of energy price. In extremely cold conditions, the price of gas may significantly improve for its heating capacities. On the other hand, the increased price of this carrier as a primary resource for gas-based plants lead to the increased price of electricity. In such cases, pressure drop in pipelines and increased consumption due to cold weathers encourages consumers to use electric power instead of natural gases for heating purposes.
- The contingency in gas pipelines is lead to the lack of natural gas for gas-based units and limiting the operational flexibility of power system by decreasing the number of fast response units.

The aforementioned factors have caused the new surveys for these two infrastructure to investigate the effect of gas infrastructure on the operation, security and planning of power systems.

2.3.1 Modeling gas network in the power system studies

Due to the grid-bounded nature of natural gas energy carrier, the node-based consumption for gas-based generation units is not real assumption. Instead it should be considered a mathematical models based on a relations in nodes consumption and their exchanges via gas pipelines. Hence, most of the early studies focused on the mathematical modeling of gas network in the power system studies. Proposed models often presented a dual of power system to model the gas network. Hence, various studies have been neglected the pressure drop of gas network and linearized the gas network equations like power system DC load flow [15]. In such models, the exchange among nodes of gas network is based on gas volume, and the pressure drop of gas pipelines is denied. On the other hand, some studies have considered the effects of pressure drop. Therefore, in these models the gas flow in gas pipelines to be dependent on the pressure drop of gas pipelines [16].

In spite of similarities, power system and gas network have a major difference in the transient dynamics. Therefore, it is not a correct assumption to consider the gas network as a dual of power system. As a matter of the fact, in power system, the system dynamic is less than a minutes long, while in gas networks, several hours are needed to achieve the steady state condition. Thus, in the modeling of this network, the maximum required demand in nodes should be considered based on their distances. This issue is particularly relevant in unit commitment studies, which has short time scales, as the steady state condition in power system might be achieved in an hour while the gas network is in its transient mode. Authors of [17] [18] have presented a linear model for gas network based on their dynamics in unit commitment study. The time required to transfer gas for one node to another one is modeled as a delay in the network mathematical model. Also [19] has utilized partial differential equations to model the dynamics of gas network in planning of power systems.

2.3.2 Units commitment problem considering gas network operation

The effect of gas network on units commitment problem has been expressed in [15]. In this article, gas networks have been modeled linearly, and only the role of gas volume exchanges have been considered. In [16], gas network has been expressed as relations between pressure and gas volume exchange between nodes to present a comprehensive model. But lack of considering the gas network transient dynamic is a drawback. Lower speed of gas compared to electricity causes the effect of an contingency or pressure drop to be lasting several hours and it take time for the system to reach another steady state operation point. Thus, in short-term and daily scheduling, gas network should be studied as a dynamic entity and not in steady state condition for each hourly snap shot. On the other hand, the role of pressure drop of gas in the output of gas turbines have also been missed in short term scheduling and planning. Hence, [17] has modeled the mentioned issues by considering the role of dual fuels and combined cycles units. In [20], stochastic programming has been used to model the uncertainties of electric network and its transfer to the gas networks.

2.3.3 Common planning of power systems and gas network

In long term, interdependency of gas and electricity infrastructures has caused mutual effects in long-term planning of these two infrastructure. Reference [21] has proposed an integrated model for generation and transmission expansion planning of gas and power networks, and according to the results, the necessity of such integrated planning has been illustrated. Also, reference [22] has considered the same approach in a competitive energy environment

2.3.4 The role of gas infrastructure on security and reliability of power system

Authors of [14] have investigated the role of gas infrastructures on power system security. To aim this goal, they have studied the role of combined cycle units and the lack of gas in gas-based power plants. This article has presents a table for output of gas-fired units in case of contingency in gas networks. After a contingency in gas network, the power system will lose some gas-fired units, therefore the Local marginal price will increase and maybe a share of demand should be interrupted or the transmission lines will be congested. To mitigate such effects, the reference states that the role of gas infrastructure in power system security should be investigated, precisely. It should be noted that, the security analysis of the paper is simple, and the role of such outage is modeled using forced outage rates. Reference [15] has been investigated the role of pressure drop and natural gas supply on the security and generation capabilities of units in power networks by modeling gas networks. To assess the effects of gas network on short term reliance of power systems, reference [22] has proposed a mixed-integer model with constraints of gas velocity in gas pipelines and reservoir capacities.

Moreover, authors of [23] have studied the reliability of gas and electric networks, and have concluded that simultaneous study of reliability of gas and electric networks is necessary, and proposed a simultaneous solution for maintenance scheduling of gas and electric networks.

2.3.5 Joint contracts of gas and electricity

Author of [24] maximizes the profit of generation units by considering joint contracts of gas and electricity. In this case the contracts are considered mostly bilateral and based on the spot market. Authors of [25] and [26] have studied the markets of gas and electricity in Colombia and Mexico, and a review of the role of gas market on expansion planning of electric network has been introduced. By considering the price of gas and maintenance costs, [27] has investigated the role of gas contracts on maintenance scheduling of generation unit. In [28], the competition of gas-based plants in the electricity and gas markets has been modeled based on the uncertainties of renewable energy resources and demand. In this regard, the role of market power of gas suppliers on the electricity market price has been investigated in [29].

2.4 Integrated models for dependent energy carriers

With the restructuring in energy sector and representation of demand as an effective player in the interaction of power system, the face of energy systems studies has been changed. Employing new energy converters in the demand side has given more flexibility to the demand for substituting its energy consumption between energy carriers and integrates the energy system in the demand side which was previously separated. For highly interdependent energy infrastructures, independent management of energy carriers is not feasible, and thus their simultaneous study receives more attention. The existence of various energy infrastructures in an integrated energy system and their simultaneous study offers the following capabilities to the decision makers:

- Flexibility in supply side: with the deployment of various energy carriers, several paths are created for the delivery of required energy to the end users.
- Reliability in demand side: although the effects of contingencies may pass along different infrastructures in integrated energy system, the presence of various paths for supplying the demand in case of contingency, will increase the total reliability of system.
- Utilizing the synergy effect: the existence of various energy carriers with different functional capabilities make a great opportunity for each carrier to mitigates its risk of operation. For instance, gas can be easily stored in high volumes, while electricity can be instantly transmit to use in farthest locations. These capabilities can put to service in complementary manner; the capabilities of a hybrid energy system from two carriers is definitely higher than the capability of a single system.
- Decentralization: with this approach, and through the advantages that this system achieves, centralized management and planning can be partially – or even completely – prevented, and the whole system turns to more distributed models, and consequently, decreasing the threat of contingency and operation limits for utilities.

2.5 Component modeling of MES

In the recent studies, the main goal of system managers is delivering the required service to the end users and the type of energy carrier to aim this goal is less of a concern. As the first step researches propose a new models to consider an integrated energy system instead of independent ones. The project of “Vision of Future Energy Networks” in ETH Zurich University was one of the first attempts to model integrated energy systems through defining the concept of “Energy Hub systems” as a model. Further researches in this university led to the conceptual model of this system, and the model was applied to the various studies of energy system. Other research institutes and universities including Waterloo University, University of Michigan and TU Delft became interested in the topic and conducted their own versions of the study. University of Politecnico di Torino further expanded the models, and the Matrix Modeling was introduced, which was similar to the energy hub model but contains more considerations about input and output energy carriers. Furthermore, the energy system was modeled as a balance of energy carriers in operation nodes.

In this regard, reviewing the literature of this field leads us to the following broad categorization of main models:

- Energy hub systems;
- Matrix modeling;
- Nodal energy balance model.

The common issues in all of the models is the categorization of energy systems into 2 major parts of operational centers and interconnectors.

2.5.1 Mathematical modeling of operation centers

Operation centers are a set of energy elements (energy sources, converters and storages) that convert input energy carriers to the output energy services. Figure 2.3 illustrates an operation center. The following points have been assumed in the references for modeling an operation center [11]

- Losses only occur within converters and storages, and other elements are completely efficient.
- The energy flow is uni-direction in the operation center, from input to output (services).

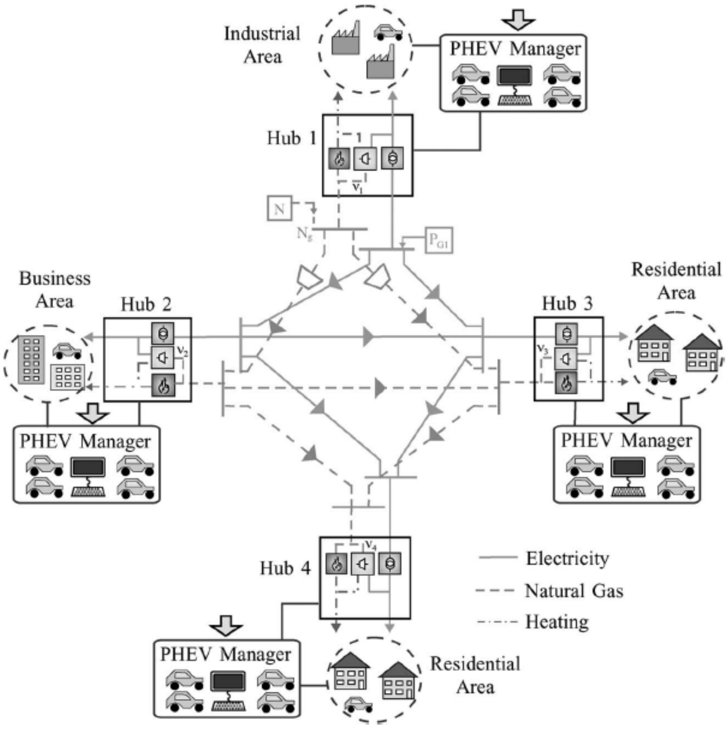

Figure 2.2: MES structure consists of operation centers and interconnectors.

- Dynamical differences of infrastructures in the operation centers are neglected, and the system is considered to be in steady-state condition.

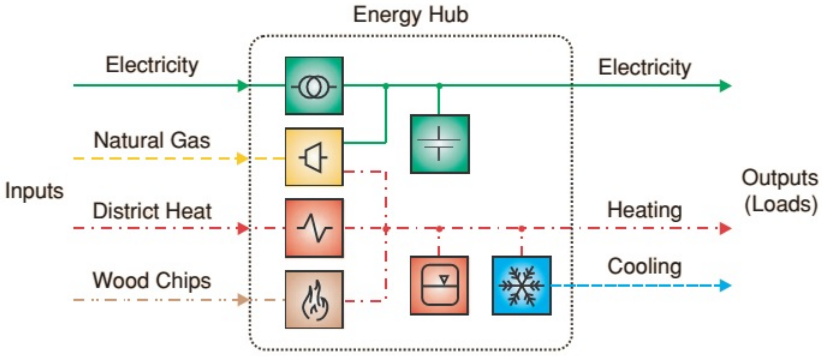

Figure 2.3: Schematic of operation center including, components, input vectors, and output vectors.

2.5.2 Mathematical modeling of energy interconnectors

The interconnectors physically are the energy pipelines or transmitters that carrying various energy and are extended all over the MES. As mathematical modeling point of view interconnectors demonstrate the manner of energy exchange between operations centers. In the recent years, attempts have been focused towards integration of energy carriers in the transfer levels. Among these, the following are highlighted [30]

- Super-cables: the main idea behind this scheme is based on transfer of high power by superconductors that are cooled by hydrogen. In this method, not only the electricity is transferred, but also hydrogen are displaced as a primary energy carrier and source of fuel cell;
- Ice fuel: the purpose of this project is the joint transfer of hydrocarbon fuels, electric power and data;
- Recovering heat from forced-cooled power cables has also been discussed. A study carried out in the Swiss network has shown that the use of this heat is only energetically attractive in a limited number of circumstances.

The future prospects of energy networks in figure 2.4 has been proposed as a scheme to jointly transfer electricity and hydrogen. The important point about this design is utilizing waste heat from electric power as the driver for hydrogen or natural gas.

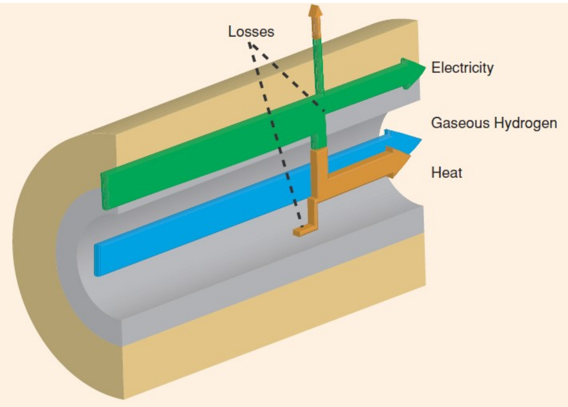

Figure 2.4: Illustration of the Energy Interconnector with electric and hydrogen transmission as well as waste heat reuse.

Mathematical models for energy Interconnector can be studied from two points of view. In the first perspective for MES, although various carriers exist, they are utilized separately in transferring, and thus every carrier is presented separately [1]. In the next perspective, the model is based on mutual interaction of carriers that are transferred together. Although in the joint transfer condition, the overall efficiency of energy systems is increased, it adds critical constraints to the operation problem of system [31].

2.6 Research trends in MES

Various researches have been conducted about modeling and studying MES. Geidl et al. [32] proposed an integrated model for this kind of networks as an energy hub. Following this model, further studies and model developments have been surveyed, some of which have been summarized as follow:

- From operation centers point of view:
    - Optimal energy dispatch in operation centers;
    - Reliability assessment in operation centers;
    - Security of supply in operation centers;
    - Energy efficiency solutions in MES;
    - Novel frameworks for urban planning considering energy system issues;
    - New approaches for modeling the demand side resources in MES framework;
        - Demand response;
        - Plug-in electric vehicles;
        - Renewable resources e.g. wind and photo-voltaic arrays;
- From energy interconnectors point of view:
    - Optimal power flow in MES;
    - Analyzing the energy exchange pattern between the European countries;
    - Interconnectors modeling;
- Modeling the energy interaction in MES:
    - Decentralized control of MES components;

- Production portfolio and risk management in MES.

As it is explained, the references proposing integrated models consider the partitioning of the MES into two parts: 1) operation centers; and 2) interconnectors. In these studies, the input and output energy carriers are considered individually. Regarding the modeling of the system, two main approaches have been previously adopted for comparing the solutions in MES.

The first group of researchers does not consider the demand side energy converters and models the network just before end use [32], [33]. The second group [34] models networks with energy converters at the end service level with high resolution, but in a very limited area such as a household.

In [33], a matrix model is proposed considering the same input and output vectors, showing how the models of the individual components can be aggregated to obtain the matrix model of the overall energy system. However, as the penetration of smart technologies grows in the system, the input and output vectors of the MES will no longer be only composed of individual components [13]. In fact, various devices that can use different sources of energy for producing the same output service are employed by the end users.

Then, the output of the MES will depend on these devices and the consumers' behavior on utilizing them. As a result, the effects of the consumers' behavior and the randomness associated to it have to be considered.

2.6.1 Optimal energy dispatch in operation centers

After developing the comprehensive models for integrated energy system, reference [35] has proposed a framework to optimal dispatch of an operation center. In this regard, this article has modeled energy converters and storages by use of their energy efficiency and dispatch variables. After that the optimal solution was found considering energy price for input energy carriers and consumption pattern of end users. In this model the heat storage was a dynamic component that enforce a time dependency to the model.

Furthermore, references [36] and [37] have optimized expected profits and mitigate the operational risks of operation center manager by applying a control method and forecasting some input parameters. Reference [37] has presented an operational method based on the intermittent nature of renewable resources. Furthermore, authors of [36] have optimized the energy consumption of household operation center. The authors have considered this program as demand response program, due to the changes in the pattern of residential electricity consumption based on real-time prices.

Reference [34] has also optimized the energy consumption in residential operation centers by proposing a mixed-integer optimization model. In this regard, this article has analyzed a big set of common residential demands in smart environment and in the form of energy hubs.

2.6.2 Optimal energy flow in energy corridors

In the all of proposed models for integrated energy systems the mathematical model of interconnectors are separated from operation centers. If the energy carriers are not transferred together through a integrated energy pathway, the relations are not different from traditional energy flow for each energy carrier. But if advanced technologies are employed to simultaneous deliver of various energy carriers, the new operational constraint for energy flow should be added to the previous ones. Reference [30] has broadly modeled such features. Although the presented models are very innovative, it should be noted that in case of simultaneous transfer of two energy carriers, other issues rather than the complexity of design and operation persist. The existence of two carriers in one place lead to geographical dependency between them. In case of an geographically-related contingencies (e.g. natural disasters), both carriers are lost, which makes these studies even more complicated. These studies are thus necessary for the development of such technologies; a matter that this article has missed.

From the traditional standpoint, reference [38] is the first study to present a model for optimal energy flow between operation centers. For this purpose, the relations of gas network and electricity were linearly (without considering changes of pressure and voltage) added to the equations of energy hubs. This model has been further expanded and developed in [34-36], and the effects of pressure and voltage has been modeled. Reference [39] has modeled Hydrogen and heat flux that the proposed models are completely similar to the nonlinear constraints of gas network. Moreover, references [40] and [41] have extracted marginal prices of different carriers for different hubs by optimal energy flow. This price can be used for expansion planning of energy carriers and optimal placement of energy converters. In addition, A new solution based on heuristics methods have been proposed in [42] for optimal energy flow problem to ensure the fast convergence of solution.

It should be noted that, the state of system in all the mentioned literature is presumed to be steady state condition. This assumption is only correct for temporal projection of network, and momentary distribution of demand. But if the model is expanded to utilize these relations for a simulation over some consecutive time intervals, the different dynamics of the infrastructures should be accounted for.

2.6.3 Reliability and security of MES

To supply an energy carrier or to offer an energy service, MES utilizes various paths. This matter increases both the security of supply and reliability of energy delivery. Due to the interdependency of carriers, contingency in an infrastructure propagate to another, i.e. every infrastructure may take damage from another infrastructure. In this situation different dynamics of infrastructures makes reliability studies of MES more complicated, as the propagation of an contingency from one carrier to another should be studied based on the carriers flow dynamics. For instance, it may take hours for an contingency in gas network to disrupt the activity of gas-to-electricity converter. Furthermore, considering a gas storages in operation center, may lead to the output reduction of a gas-fired unit instead of its outage. This issue complicates the studies of system elements in case of contingency.

Authors of [43] and [44] have focused on the reliability of energy hubs. The main assumption of these researches is that the behaviors of a hub system can be modeled based on Markov chains. Reference [43] has also investigated the role of storage in reliability of systems. Additionally, [45] has studied the reliability of energy hubs, but has modeled generation units discretely, and has accounted for a greater range of operational conditions in the reliability assessment study.

Reference [46]] has studied security issues of MES. This reference has investigated cascading failure in energy hub systems, with a focus on propagation of failures from one carrier to another. The same author has employed Model predictive control (MPC) to prevent cascading failures in [47].

2.6.4 Investment and expansion vision in MES

Along the researches on the structure of future energy systems, some literatures have focused on the ways to achieve and develop on these grounds. In this regard, references [48] and [49] have planned technological development portfolios in very long-term time horizon to provide required energy services in future perspective. From an investor viewpoint, reference [8] has evaluated the investment portfolio in MES including converters and storage resources. Reference [50] has planned the expansion of energy hub components based on the reliability indexes. Given the high importance of storages, reference [7] has studied the optimal placement of these resources in energy hubs.

2.6.5 Integration of DERs in MES models

With the increased share of distributed generation and demand side energy resources, their roles have become ever more important in the studies of power systems. But considering the concept of MES, operation centers cannot be categorized as power systems sectors in the form of generation, transmission, and distribution. An operation center may consume an energy carrier while supplying another energy carrier. Also, it may use an energy carrier at one time period, and produce the same type of carrier in another time period. In this regard, resources of operation centers can be categorized in three groups from viewpoint of MES concept:

- Resources that are based on changes in the demand pattern, including demand response and energy efficiency;
- Resources that can be generated locally (mostly renewable), i.e. direct conversion of energy from one source to a carrier or service;
- Resources that are originated from the flexibility between energy carriers, which are obtained by the conversion of one carrier to another, or storing

a carrier;

One of the main assumptions in the energy hub model is the unidirectional energy flow; therefore after integrating RER in [51] the model has been modified to inject the surplus energy to the upstream energy network. Moreover, The stochastic nature renewable units have been overlooked in this research. On the other hand, the capability of MES to serve ancillary services is discussed in [33] and the new concept of multienergy/power arbitrage has been developed for considering reserve in MES. In order to analyze the impact of a high penetration wind resources on interdependent MES, a robust optimization approach is used in [52]. Numerical results determine the role of the power system to mitigate the uncertainty of wind resources by substituting the energy demand of one carrier with the demand of another energy carrier. On the other hand, authors in [53] have shown that it is possible to increase the utilization factor of wind resources in power system operation with MES facilities. In other words, the power system acts as a link between RER and MES that can help decreasing the uncertainty of these resources by using the inherent flexibility of MES.

Reference [6] considers the effect of price variation on energy consumption in operation centers. In this case end used has a constant energy consumption and price variation altered the inputs of operational centers. Reference [8] gives a broader attention to the role of demand response programs in energy hub systems, and adds a new coefficient matrix to the conversion matrix. This matrix is multiplied to the substituted load between energy carriers, and results the new load pattern. In [4], the substitution of load has been modeled as a consumption strategy. Furthermore, in [54], in addition to this model, flexible heat load and interruptible load have been modeled as other strategies. Reference [48] assesses the exergy (energy consumption) induced to the hub using The energy content of the carrier and to find the most efficient combination of energy carrier to gain the required energy services. In addition, a game-based approach among energy hubs for DR provision is suggested in [16].

For the integration of PEVs in the energy hub framework, the internal interaction of PEVs has been modeled in [55] as an independent energy hub. The model has been developed to consider integration of PEVs in G2V mode as a manageable load for optimal operation [56] and as an ancillary service provision (frequency control) [57] in the energy hub system.

Although these references are almost the sole references that survey the operational behavior of PEVs in MES, there are plenty of references that report the role of PEVs integration in power system studies. Controlling the PEVs to maximize the income from frequency regulation has been described in [58]. In [59], a heuristic strategy for PEVs charging has been reported to provide the regulation service. In [60], a business model has been reported in which the PEV aggregator has been modeled as a load aggregator that purchases energy from the electricity market with no control over the PEV charging. A conceptual framework to operate the aggregated PEVs in the V2G mode has been proposed in [61]. In [62], a linear programming model has been presented to optimize the charging plan for PEVs by minimizing electricity costs and battery wears. In [63], a heuristic algorithm has been presented to control PEV charging in response to time-of-use prices in a traditional power system. In [64], an optimization algorithm has been proposed to manage the individual charging of PEVs to decrease the deviation costs and to ensure a reliable supply of manual reserve. A behavioral model for PEVs' aggregator in reserve and energy markets has been presented in [65].

In [66], an optimization method has been presented to support the participation of the PEV aggregator in the day-ahead spot and secondary reserve market. In [67], the behavior of PEV aggregator has been modeled as a linking agent between PEV owners and the electricity market by using a stochastic multilayer agent-based model.

Although these models have precisely considered the behavior of aggregator and market characteristics, there are some differences between PEVs' aggregator and PL owner behavior. The PEVs' aggregator has wide knowledge about its contracted PEVs, e.g., the number and battery characteristics, but the knowledge of PL owner is mostly about the traffic pattern in its PL zone. On the other hand, one of the goals of this thesis is to investigate the role of PL in MES and the impact of its behavior on other elements' operational characteristics. Therefore, in this thesis, the PL behavior is modeled based on the aggregated PEVs' traffic pattern in PL and the main objective is to fit this model with an energy hub approach.

2.7 Decision making frameworks in energy systems

The main goal of this thesis is designing a decision making framework for energy players who can trade more than one energy carrier in the MES. As the research background in this section the general decision making frameworks those are utilized in MES and power system research areas are reviewed.

2.7.1 Control strategies in MES

in the research literature, controlling a MES has been studied from two points of view:

- Controlling the components of an operation center;
- Controlling a set of operation centers in a MES.

Some references have utilized model predictive control approach as control method for both approach. Considering the prediction for the future of the system for a planning horizon, the optimal combination of inputs is selected to achieve expectations. For the first perspective, reference [37] has utilized this method to select the optimum control approach to mitigate the uncertainties of decision making in the presence of energy storage. Reference [36] has extended this approach, and has employed it for optimal control of residential energy hub in changes of price of energy carriers.

For the second perspective, authors of [11] and [68] have modeled a decentralized controller based on a set of information transition between operation center. The purpose of such decentralized method is to achieve the same result of assumed centralized control. In addition, reference [47] has utilized model predictive control to prevent cascading failures and contingencies in energy hub systems.

Furthermore, authors of [69] have proposed a decentralized control method in MES, in which different components can optimize their cost function by exchanging a set of basic data. Although the model has considered various features of MES from technical point of view, the economical aspects have not been modeled properly. In this model the coupling signals among energy hubs as MEP is exchanging energy but in reality and competitive environment the coupling signals among MEP will be the energy price.

The main deficiency of these researches is not considering the real interaction environment of energy players in MES. In these models the players share their entity private information with rivals to reach the minimum cost operation point. This interaction structure in energy system, drawing back to traditional systems and integrated control based on reducing costs and all players participation is impossible. The main issue in this system, is the level and type of information that players are willing to share with rivals. Therefore, architecting an efficient energy interaction structure and determine the role of each energy player in this structure is the goal of this thesis.

2.7.2 MGs cooperation environment

In previous studies, the microgrid (MG) concept has been developed to cover some aspects of the future energy systems. The main feature of MG is the stand-alone operation capability in contingency modes that can increase the system's reliability indices. However, this capability needs the deployment of energy resources with more capacity than the average consumption of MG. These resources provide the opportunity to trade the energy surplus in a normal operation mode. Therefore, MG is able to increase the operator' total profit as well as their own. Likewise, MG can be considered as MES. However, MG is reliability-oriented while MES is related to the enhancement of the system's efficiency. Due to the above-mentioned similarity, MG studies have been also surveyed.

The cooperation between MGs is modeled in [70, 71, 72]. Cooperation of several MGs is modeled as cooperative power dispatching algorithm in [70] to power sharing with the main grid. Energy resource scheduling of a set of MGs is modeled using multi-agent systems in [71]. A decentralized optimal control algorithm is presented in [72] to energy management in distribution grid with multi-microgrids. Moreover, the cooperation between Disco and MGs is evaluated using system of systems (SOS) framework in [73] and [74]. In the proposed framework in these papers, Disco and MGs are considered as the independent entities and cooperation between them is modeled in a hierarchical framework. At first, all MGs receive required parameters from Disco and solve their objective function individually. Then, Disco receives required parameters to solve its objective function from MGs. This process is continued until the convergence condition which is defined for this problem is satisfied. Since most of the mentioned papers focused on the technical issues, the economical aspects of cooperation between decision makers are not modeled properly in the literature.

On the other hand, the participation of Disco in wholesale energy and reserve markets are investigated in many literatures [75, 76, 77, 78, 79, 80]. In [75] a two-stage framework is presented to model the behavior of Disco in day-ahead and real time markets. At the first stage, Disco decides about participation in day-ahead market and its resource scheduling. These decisions are used in the second stage of the Disco problem in which Disco participate in real market with optimal scheduling of resources. The proposed framework for operation of Disco in [75] is extended with notice to uncertainties of real-time market prices and load in [76]. Participation of Disco in both energy and reserve markets is investigated in [77, 78, 79, 80]. In these papers, Disco includes DGs and interruptible loads (IL). Therefore, the optimal decision of Disco for participating in competitive markets is determined with respect to the optimal scheduling of these resources.

In addition, reference [81] proposes a scheduling framework for a single MG that is equipped with a combination of cooling, heating and power (CCHP) units and RER. Different behaviors of CCHP's energy carriers and the uncertainty of RER are covered by a multi-time scale framework along with the time horizon. Moreover, for a set of MGs, the authors in [82] have used an agent-based framework to model the cooperation environment among MGs. Regarding this topic, an energy retail market is proposed in [83] to fill the gap between the wholesale market and the demand-side players (i.e., MG). Furthermore, the authors in [84] have developed a multi-leader multi-follower Stackelberg game to manage energy trading among MGs analyzing its equilibrium point. Employing more than one energy carrier has changed the behavior of MEP compared to MG operators. Thus, new models for evaluating the behavior of MEP in future energy systems are required.

2.8 Future Energy System Perspective

Figure 2.5 shows the course of evolution for the energy system from situation to a fully integrated MES. Multi-energy players (MEP) play a crucial role in this vision.

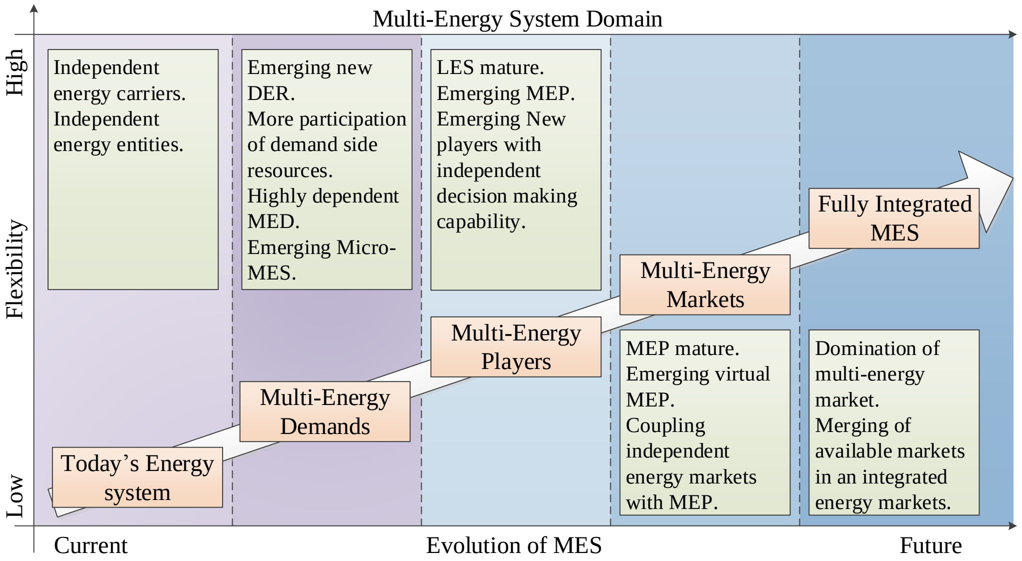

Figure 2.5: Course of evolution for MES from today's energy system to fully integrated MES.

2.8.1 Emerging energy players

MEP are defined as energy players who can trade with more than one energy carrier to increase their total profits and mitigate their operational risks. MEP can link individual energy markets and, consequently, introduce themselves as a source of flexibility to market managers (figure 2.6). Therefore, increasing the share of MEP in each energy market brings opportunities and challenges for both MEP and individual market operators and affects their decision-making parameters in the short- and long-term.

In this regard, multi-energy demands (MED) as small scale energy players appear in the system, which can substitute its energy consumption between energy carriers. Their flexibility forces the independent energy carriers managers to operate and plan their systems based on the interaction with other energy carriers and resources. For

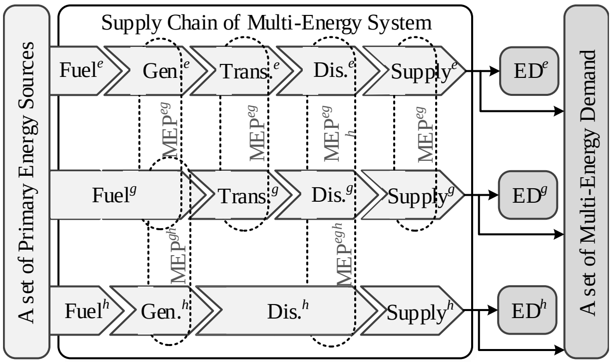

Figure 2.6: Supply chain of MES and the role of MEPs.

this reason, firstly, these managers have to consider MEDs flexibility in their studies, secondly, enhance their flexibility and introduce themselves as local energy systems (LES) with a considerable amount of smartness.

2.8.2 Integrated energy markets

Emerging multi-energy players can exchange energy in various forms and prefer to trade energy packages (consisting of more than one form of energy) to mitigate their risk and enhance their security of supply. In this condition, new energy markets will be encouraged to be established that enable trading various energy packages among multi-energy players. Expansion of multi-energy markets will motivate multi-energy players to enhance their flexibility and their share in those markets. Furthermore, some players can also participate in more than one multi-energy market to exploit more benefit from arbitrage among markets. An increase of these activities will make multi-energy markets more dependent. This dependency initiates the integration of these markets from organizational and technical or only financial points of view. The vision for this environment is a fully competitive integrated energy system that provides highly secure and cheap energy services for all users based on their requirements regardless of the energy carrier type.

2.9 Fractal structure for MES

MEP may have different functionalities and decision making frameworks based on their flexibility to switch between energy carriers and utilizing their local energy resources. These features fit a multi-layer structure for MES, where, in each layer, MEP with the same specifications interact with each other through various energy carriers. The relation between the layers is through the aggregation of various lower-level MEP in the upper-level MEP. In other words, the upper-level MEP aggregates and serves a multiple number of MEP from the lower levels. However, the MEP aggregator finds the equilibrium with conflicts between the objectives of the MEP in different layers. In the lower levels, small-scale MEP prefer to cooperate with each other in order to increase their profits and satisfy their energy requirements. On the contrary, larger-scale MEP compete to maximize their profits and mitigate their operational risks in the upper level. Therefore, the correlation between these two layers through an intermediate MEP should be modeled, this being the purpose of the study. Figure 2.7 the fractal structure that is considered in the thesis. Some of the main characteristics of this structure are as follow:

- All MEPs are able to participate and decide in the cooperation environment;
- Due to diverse characteristic of MEP, competition or cooperation in only one layer is almost impossible for all of them;
- Multi-layer structure allows MEPs to be placed in a similar layer of market power and performance;
- Every layer is a set of MEPs, and the next layer is constructed within these players. This process continues until the smallest energy players are modeled;
- To regulate the system, some lows should be put to ground for energy markets in the first layer;
- These layers are interdependent and decision on one layer influences on another ones;
- The type of interaction in every layer can be different, but in general, it can be expected that from energy markets as the first layer to the last layer that is

MED, the interaction spans from complete competition to total collaboration.

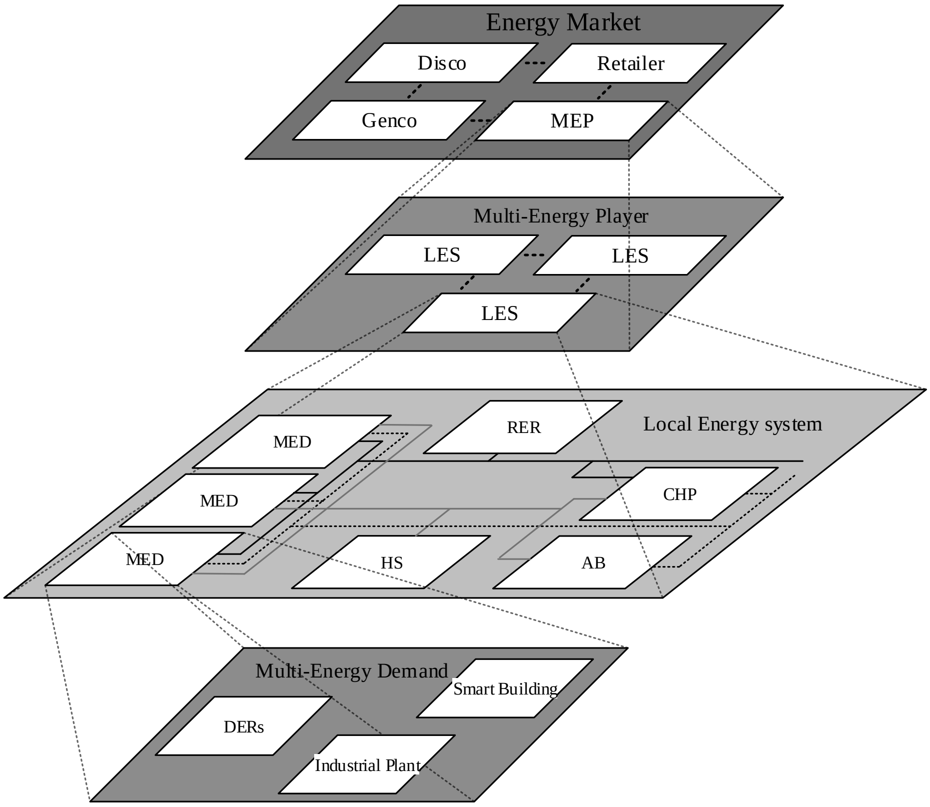

Figure 2.7: A fractal schematic of the multi-layer energy system.

As it is shown in 2.8 each energy player has its objective function and own operational constraints in the proposed fractal structure. The energy layers in this structure are energy market, MEP layer, LES layer, and MED layer, respectively. the short description of each layer is represented as follow.

2.9.1 Energy markets

Energy market is a main competition environment in proposed fractal structure for MES. The MEPs interact energy in individual or integrated energy markets to maximize their profit through competing with other MEPs or conventional energy market players.

The energy markets in this study are the networks of gas and electricity that MEPs exchange energies in them. The behavior of MEP has been modeled as a strategic

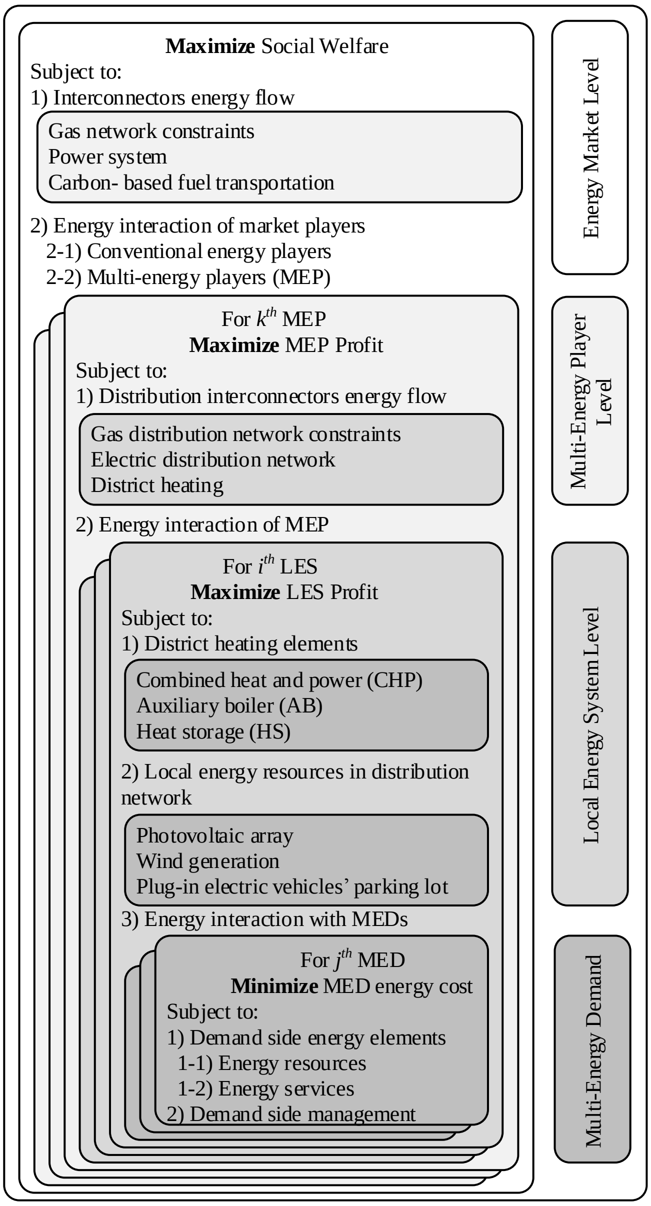

Figure 2.8: Fractal structure of MES and the role of MEP on that.

player in electricity market, and with greater penetration rate, they can change the electricity prices and behavior of other market players. But the behavior of players in gas market has been considered as a price taker player with no market power to influences prices or energy players interactions in this market. This assumption is due to long term contracts of natural gas, and existence of bulk reservoirs in gas network. This factors lead to the smooth price dynamics for natural gas, as it does not experience sudden changes in short periods of time.

2.9.2 Multi-energy players

MEP are integration of a set of LESs and consists of some bulk energy resources. They trade energy with LESs in local energy market and other MEPs in wholesale energy market

2.9.3 Local energy systems

LES is a local energy system that is equipped by medium scale energy resources and serves various energy carriers to MEDs. Moreover, local energy resources enables LES to introduce themselves as the producer of some energies in local or national level based on their resources scheduling pattern and signals of energy price. These players increase the competition in demand side and makes the system a more flexible.

2.9.4 Multi-energy demands

MED can be considered as integration of smart buildings or industrial plants that can change their energy consumption patterns during the day through small scale energy converters (e.g. micro-combined heat and power (CHP) units) and storages (e.g. heat storage and plug-in electric vehicles (PHEVs)).

2.10 Flexibility Classification in MES

Flexibility in energy systems are categorized from different aspects i.e. temporal, dimension, and domain, which are described afterwards.

2.10.1 Temporal Aspect

From temporal aspect, flexibility in MES can be categorized based on different time horizons; i.e. very long-term, long-term, mid-term and short-term. A main share of this flexibility is inherent and due to planning issues of infrastructure whereas the other share is provided by the ability of decision makers in optimum operation of equipment. These two kinds of flexibility are achievable in short-term and operation time horizon, but should be prepared in advance in longer time horizons. In short-term, it is possible to improve the flexibility of the system by a better operation; but, in long-term, the inherent flexibility can be improved by optimum expansion of energy system infrastructures. It can be concluded that there are different strategies for enhancing MES based on the temporal aspect, while strategies in longer time horizons affect the possibility of implementing strategies in shorter time horizon.

2.10.1.1 Very Long-term Flexibility

In very long-term, the flexibility is derived from changes in organizational structures and regulating new legislation. More flexibility in organizations and regulations help MEP to have more feasible options. For instance, promotion of energy markets with different clearing time help the players with different dynamics and uncertainties to decrease their participation risk and enhance their profits. Introducing new energy markets that can trade different energy carriers can help flexible MEP to make use of this opportunity and reduce their operational risk. These markets enable a flexible and stable environment for decreasing MEP uncertainty in short-term, while in long-term they will orient the system planners in utilizing the optimum energy carriers for supplying demanded energy service.

2.10.1.2 Long-term Flexibility

In long-term, expansion planning strategies of storages and converters can increase the flexibility of system in both time and energy carrier dimensions. Thus, increasing the flexibility level of the MES should be considered in planning studies. Regarding this matter, over-investment in grid nodes will be prevented. Thus, the operating cost will be reduced dramatically from two points of view; i.e. less discounted investment cost and less operation cost due to optimum use of MES opportunities.

2.10.1.3 Mid-term Flexibility

In mid-term, proper maintenance planning of energy systems will increase the chance of using all anticipated facilities in the operation period. By raising mid-term flexibility of energy systems, the share of variable generation could increase through rapid load changes in response to generation variation. This type of flexibility ensures the optimum operation of the system in the maintenance planning. Therefore, the role of investigating the carriers-based flexibility of a MES is highlighted in mid-term flexibility assessments.

2.10.1.4 Short-term Flexibility

In short-term flexibility, the infrastructure, topology and availability of all energy sub-systems are determined in advance. Thus, it is the best period to utilize all MES flexibility potential through optimum operation of the system. The energy system operator can make the best decision for serving its loads as well as minimizing the system cost. Short-term flexibility will be enhanced by the development of powerful decision making tools in the system.

2.10.2 Dimension Aspect

As it was mentioned before, MES flexibility is categorized from two points of view; i.e. time- and carrier- based flexibility. Time-based flexibility may lead to change the normal demand pattern of a specific energy carrier through shifting its demand in time. Energy storage systems and employing energy management programs are two powerful tools for enhancing this kind of flexibility. Carrier-based flexibility may lead to a change in the energy carrier load pattern, but through substituting another carrier with initial ones while the end-use service pattern remains unchanged. This kind of flexibility can be enhanced by increasing the energy converters in the MES.

2.10.3 Domain Aspect

Since different energy carriers have different domain based on their area of service; their flexibility have local, zonal or global impacts. For instance, district heating system brings flexibility for MES in a specific area whereas this flexibility may have no direct impact on other areas. On the other hand, in energy systems with energy converters that can transfer flexibility from one carrier to another, the flexibility can be extended in the system by grid bounded carriers. In return, with extension of grid bounded carriers, both local and global flexibility can be expected. Time non-conformity of flexibility in different areas can reduce system total cost by utilizing transferable flexibility. Therefore, flexibility enhancement in MES expansion planning should be homogenous in order to take benefit of all possible opportunities. This means that in a case where adjacent operation center's flexibility can be employed in a certain operation center, the over planning of this center for increasing the flexibility level should be prevented. Introducing flexibility as an independent concept helps the system managers to consider the effect of transferable flexibility among carriers and energy areas.

2.10.4 flexibility Assessment in MES

Flexibility is an abstract definition, and in this literature, a clear method to determine and measure it is yet to be expressed. But in overall, this concept can be analyzed with two perspectives in MES: (A) increase of the systems' degree of freedom; and (B) increase of the performance of system. In MES, systems are presumed to have more freedom and thus flexible that, due to their differences in decision-making structures, contributes to a greater share of local resource being demanded, or the behavior of MEP shows a more convergent pattern in the utilization of various carriers.

Secondly, the distinction between the multi-carrier energy system and other concepts of conventional systems such as micro-grids is the high efficiency of this system. In fact, the main purpose of integrating energy carriers in the form of this system is benefitting from synergy of carriers, thus contributing to the overall productivity of the system,

Chapter 3

Modeling the Operational Behavior of PEVs' PL in Local Energy System

Electrification of energy demand in systems with high penetration of renewable energy resources can mitigate environmental aspects of carbon-based fuels. Transportation system as one of the main energy consuming sectors plays an important role in this vision. Commercializing plug-in electric vehicles (PEVs) technologies (e.g., battery and charge/discharge facilities) accelerates their integration in urban areas [85].

PEVs' parking lots (PLs) are located in populated districts and equipped with charge/discharge facilities. PEVs' PLs not only serve energy services to the PEVs, but also enable bi-directional interface among a group of PEVs as a new generation of bulk ES and energy system [86]. Therefore, in future energy systems they can play as independent multi-energy players (MEPs), having an important role in a local MES as a bulk storage facility or flexible load.

This chapter aims to model the operational behavior of PEVs' PL as an element of local MES. For this purpose, MES is described as a fractal structure and modeled by an energy hub approach. As a result of the PL operational characteristics, its behavior in both energy and reserve markets is considered. The energy hub model is modified to handle the participation of MES elements in the reserve market. Moreover, a stochastic approach is applied to model the uncertainty of wind generation (WG) and the behavior of PEVs' owners in PL.

3.1 Local Energy System

The introduction of distributed energy resources (DERs) is taking a significant part in forwarding the sustainable development and hedging the problems occurring to future energy portfolios [87]. Being co-related to both loads and energy supply system, DERs can increase the opportunities to enhance the services offered to loads as well as taking more benefits of loss reduction by changing the way of power transfer [88]. As the penetration of technology grows among the devices that are used by end users, the demand side will be more capable and eager to participate in advancing the sustainable development. This process does not only help the progress of sustainable development, but also will bring more technical and economic advantages to end users.

However, utilization of these resources for achieving the sustainable development objectives necessitates the employment of smart grids in order to convert this potential possibility into actual solutions [85]. Facilitating the bi-directional relation between the user and the system operator makes it possible to utilize and operate DERs at different levels [86]. In this regard, the technological development and commercialization is increasing the availability of technologies such as small-scale CHP units and energy storage systems, which are introduced in local energy systems (LES) systems [32] to enhance the flexibility of serving a multi-energy demand (MED). As a matter of the fact, LES can be considered as an urban district that consists of medium level energy converters (ECs) and energy storages (ESs). LES receives energy from MEP and delivers energy to the MED.

3.2 Matrix Modeling of LES with Conventional Energy Components

3.2.1 Comprehensive Model of LES

The energy hub approach models MES as a coupling matrix that converts input energy carriers to output energy services [86]. Equation 3.1 shows the matrix model of an energy hub, where **p** and **l** are the vectors of input energy carriers and output energy services, respectively.

In this model, **C** is coupling matrix and relies on the ECs of energy hub. One of the main assumptions in the energy hub modeling is unidirectional energy flow in the energy hub's elements. Therefore, vector **k** enables the model to inject energy hub's surplus energy into the upstream system [55].

$$\begin{bmatrix}\mathbf{C}\end{bmatrix}\begin{bmatrix}\mathbf{p}\end{bmatrix} = \begin{bmatrix}\mathbf{l}\end{bmatrix} + \begin{bmatrix}\mathbf{k}\end{bmatrix} \tag{3.1}$$

The expansion of 3.2 showing the relation between input and output carriers is modeled as.

$$\begin{bmatrix} L_{\alpha t} \\ L_{\beta t} \\ \vdots \\ L_{\omega t} \end{bmatrix} + \begin{bmatrix} k_{\alpha t} \\ k_{\beta t} \\ \vdots \\ k_{\omega t} \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & \dots & C_{\alpha\omega} \\ C_{\beta\alpha} & \dots & C_{\beta\omega} \\ \vdots & \ddots & \vdots \\ C_{\omega\alpha} & \dots & C_{\omega\omega} \end{bmatrix} \begin{bmatrix} p_{\alpha t} \\ p_{\beta t} \\ \vdots \\ p_{\omega t} \end{bmatrix} \tag{3.2}$$

Each element of the matrix **C** denotes the conversion of one carrier into another and is composed of two categories of parameters: the first category includes coefficients depending on physical characteristics of the system and of the energy converters, such as the efficiencies (η_α).

The second category includes the decision variables, here denoted as weighted energy contribution variables ($v_{\alpha,t}$), which indicate the energy distribution among the energy converters in 3.3. In fact, these are continuous variables that determine the share of each energy carrier in the total energy demand. Only in very simple cases the decision variable can be considered as binary, representing a switch between two possible alternatives to supply the demand needed for a given service by using two energy carriers. Hence, the entries of the matrix **C** can be expressed as follow:

$$C_{\alpha\beta} = f(v, \eta) \tag{3.3}$$

As Arnold and Andersson [68] and Kienzle and Andersson [48] have explained, the role of energy storages can be modeled through some changes in the coupling matrix and the input energy vector. Regarding the energy carriers dependency, the fact that the user can resort to individual storages causes the definition of an extended input vector ($\mathbf{p_n}$) with respect to the input vector **p** used in the case where no storage exists.

On the one hand, the amount of energy consumed from storages (vector $\dot{\mathbf{e}}_{\mathbf{s}}$) is added to the input vector. On the other hand, the coupling matrix of the storage ($\mathbf{S}$), which represents how changes in the amount of energy stored will affect the system output, is added to the total system coupling matrix. Hence, the combined model is shown as 3.4.

$$\begin{bmatrix}\mathbf{l}\end{bmatrix} + \begin{bmatrix}\mathbf{k}\end{bmatrix} = \begin{bmatrix}\mathbf{C} & -\mathbf{S}\end{bmatrix} \begin{bmatrix}\mathbf{p_n} \\ \dot{\mathbf{e}}_{\mathbf{s}}\end{bmatrix} \tag{3.4}$$

In the modified model, $\dot{ES}\,^{\cdot}$ is the change in the stored energy and can be computed from 3.5 and 3.6 by considering the charge/standby conditions or the discharge conditions.

$$\dot{es}_{\alpha,t} = es_{\alpha,t} - es_{\alpha,t-1} \tag{3.5}$$

$$\eta_{\alpha}^{r} = \begin{cases} \eta_{\alpha}^{r\,(+)} & if\ \dot{ES}_{\alpha,t} \geq 0\ (Charge/Standby) \\ 1/\eta_{\alpha}^{r\,(-)} & if\ \dot{ES}_{\alpha,t} < 0\ (Discharge) \end{cases} \tag{3.6}$$

3.2.2 Detailed Model of LES

Figure 3.1 demonstrates a LES equipped by a CHP unit, wind generation (WG), auxiliary boiler (AB), and heat storage (HS). Input energy carriers are electricity and natural gas ($p_{\omega,t}^{in} = [w_{\omega,t}^{in} + w_{\omega,t}^{wind} \quad g_{\omega,t}^{in}]$), while output energy services are electricity and heat ($l_{t}^{MED} = [W_{t}^{MED} \quad Q_{t}^{MED}]$), and surplus energy services are electric power($k_{\omega,t}^{inj} = [w_{\omega,t}^{inj} \quad 0]$). Equation 3.7, shows the energy hub model of LES considering its interaction with MEP and MED.

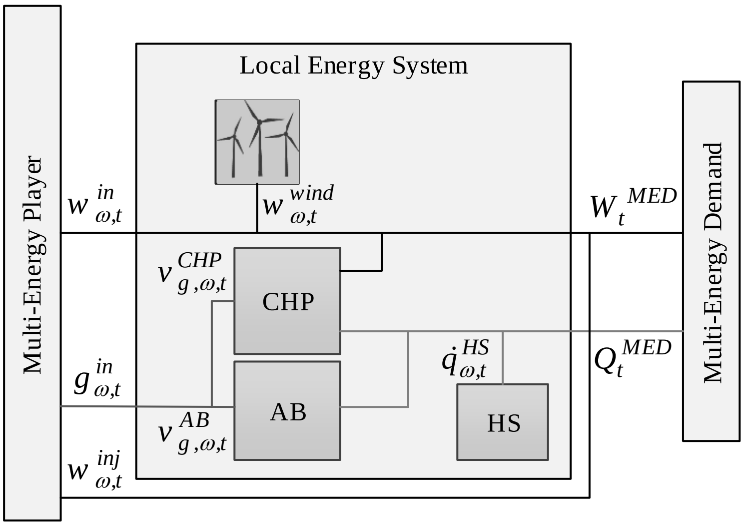

Figure 3.1: Local energy system schematic and energy interaction with MEP and MED

$$\begin{bmatrix} 1 & v^{CHP}_{g,\omega,t}\eta^{CHP}_{e} & 0 \\ 0 & v^{CHP}_{g,\omega,t}\eta^{CHP}_{h} + v^{AB}_{g,\omega,t}\eta^{AB}_{h} & 1/\eta^{HS}_{h} \end{bmatrix} \begin{bmatrix} w^{in}_{\omega,t} + w^{wind}_{\omega,t} \\ g^{in}_{\omega,t} \\ \dot{q}^{HS}_{\omega,t} \end{bmatrix} = \begin{bmatrix} W^{MED}_{t} \\ Q^{MED}_{t} \end{bmatrix} + \begin{bmatrix} w^{inj}_{\omega,t} \\ 0 \end{bmatrix} \tag{3.7}$$

3.2.3 Operational Constraints

In the operational problem of LES each elements has its operational constraints. The constraints are generally expressed in terms of capacity. As such, in order to check the constraints it is needed to express the average power values in the relevant time subinterval.

Let us consider for each hour the number n_τ of uniformly spaced time subintervals (e.g., $n_t = 4$ for 15 min subintervals) [46]. Hence, the energy input corresponds to the average power as in 3.8 and 3.9. The same relation holds between any average power and energy quantities. The constraints for system operation are formulated as follows.

$$w_{\omega,t} = w_{\omega,t} \Big/ n_t \tag{3.8}$$

$$g_{\omega,t} = g_{\omega,t} \Big/ n_t \tag{3.9}$$

Input Carriers Constraints: Each energy carrier has a supply limit that may be due to the power amount from the supply source or power transmission limits.

$$0 \leq w_{\omega,t} \leq \overline{w}_{\omega,t} \tag{3.10}$$

$$0 \leq g_{\omega,t} \leq \overline{G}_{\omega,t} \tag{3.11}$$

Operational Constraints of the CHP Unit: Regarding manufacturing characteristics of the CHP unit, they face limits in the amount of electrical power output $w_{\omega,t}^{CHP}$ or heat power output $q_{\omega,t}^{CHP}$. Furthermore, the CHP unit should be operated in the allowed heat to power ratio zone.

$$\underline{W}^{CHP} \leq w_{\omega,t}^{CHP} \leq \overline{W}^{CHP} \tag{3.12}$$

$$\underline{Q}^{CHP} \leq q_{\omega,t}^{CHP} \leq \overline{Q}^{CHP} \tag{3.13}$$

$$\varphi_{\omega,t}^{CHP} = q_{\omega,t}^{CHP} \Big/ w_{\omega,t}^{CHP} \tag{3.14}$$

$$\underline{\Phi}^{CHP} \leq \varphi_{\omega,t}^{CHP} \leq \overline{\Phi}^{CHP} \tag{3.15}$$

Operational Constraints of the Auxiliary Boiler: Output heat of AB should be in its upper and lower operational bounds.

$$\underline{Q}^{AB} \leq q_{\omega,t}^{AB} \leq \overline{Q}^{AB} \tag{3.16}$$

Operational Constraints of Heat Storage: Rate of HS interaction with LES should be within operational limit

$$\left|\dot{q}^{HS}_{\omega,t}\right| \leq \Gamma^{HS} \tag{3.17}$$

$$\underline{Q}^{HS} \leq q^{HS}_{\omega,t} \leq \overline{Q}^{HS} \tag{3.18}$$

Constraints on the Weighted Energy Contribution Variables: v is the dispatch factor and shows the share of each energy element from input energy, and its amount should be between 0 and 1.

$$0 \leq v \leq 1 \quad \text{for all weighted energy contribution variables} \tag{3.19}$$

$$v^{AB}_{g,\omega,t} + v^{CHP}_{g,\omega,t} = 1 \tag{3.20}$$

3.3 Comprehensive Model of LES Considering PEVs' PL

In the energy hub, PL behaves as a storage system with uncertainties in its total capacity and SOC in each hour. The uncertain behavior of PL has been modeled by the stochastic approach described in the Appendix. On the other hand, PL has an interaction with MES as well as PEVs. The PLs electric energy interaction with MES can be modeled by adding a new row in matrix $\dot{\mathbf{e}}$ that represents the share of PLs SOC changes in the output of energy services.

$$\left[\dot{\mathbf{e}}^{\mathbf{new}}\right] = \begin{bmatrix} \dot{\mathbf{e}}^{\mathbf{old}} \\ \mathbf{s\dot{o}c}^{\mathbf{PL}} \end{bmatrix} \tag{3.21}$$

In addition, electric reserve is considered as an output energy service of MES that can be served to the upstream system. Therefore, new rows ($\mathbf{r}^{\mathbf{inj}}$) are added to the matrices $\mathbf{l}$ and $\mathbf{k}$, but due to sole usage of reserve in upstream network, the amount of reserve array in matrix $\mathbf{l}$ is equal to zero.

$$\begin{bmatrix}\mathbf{l^{new}}\end{bmatrix} = \begin{bmatrix}\mathbf{l^{old}} \\ \mathbf{0}\end{bmatrix} \tag{3.22}$$

$$\begin{bmatrix}\mathbf{k^{new}}\end{bmatrix} = \begin{bmatrix}\mathbf{k^{old}} \\ \mathbf{r^{inj}}\end{bmatrix} \tag{3.23}$$

By adding new rows in the output, the matrices **C** and **S** will be modified to determine the share of each element on the new output energy service (electric reserve). In the modified model, the converter share can be modeled as the capability to maximize output electricity. However, for electric ES it depends on its rated output power and its stored energy in each hour. Determining the reserve service for electric ES needs new rows in p to show the share of electric ES for serving reserve to the MES as an input virtual energy carrier.

$$\begin{bmatrix}\mathbf{p^{new}}\end{bmatrix} = \begin{bmatrix}\mathbf{p^{old}} \\ \mathbf{r^{ES}}\end{bmatrix} \tag{3.24}$$

$$\begin{bmatrix}\mathbf{C^{new}}\end{bmatrix} = \begin{bmatrix}\mathbf{C^{old}} & \mathbf{0} \\ \mathbf{C^{EC}} & \mathbf{C^{ES}}\end{bmatrix} \tag{3.25}$$

$$\begin{bmatrix}\mathbf{S^{new}}\end{bmatrix} = \begin{bmatrix}\mathbf{S^{old}} & \mathbf{S^{PL}} \\ \mathbf{0} & \mathbf{0}\end{bmatrix} \tag{3.26}$$

where,

$\mathbf{C^{old}}$	coupling matrix that states the conversion of inputs energy carriers into outputs energy services;
$\mathbf{C^{EC}}$	coupling matrix to show the share of ECs in output reserve, which is based on the efficiency of ECs;
$\mathbf{C^{ES}}$	coupling matrix to show the share of storage in output reserve, which is based on discharge efficiency of storage;
$\mathbf{S^{old}}$	storage coupling matrix that shows the changes of output energy service versus changes in stored energy;
$\mathbf{S^{PL}}$	coupling matrix to show the share of PL in output reserve, which is based on discharge efficiency of PL;
$\mathbf{M}$	matrix of vacant capacity of ECs;
$\mathbf{U}$	Decision making matrix with binary arrays, determining the participation of each converter in output reserve.

In order to produce $\mathbf{C^{EC}}$, each array of $\mathbf{M}$ is divided by the corresponding array of $\mathbf{P^{old}}$ and then multiplied by the array of $\mathbf{U}$.

$$\mathbf{C^{EC}} = \frac{\mathbf{M}}{\mathbf{P^{old}}}\mathbf{U} \tag{3.27}$$

By substituting the modified terms in 3.1, the system's new equation is

$$\begin{bmatrix} \mathbf{C^{new}} & \mathbf{S^{new}} \end{bmatrix} \begin{bmatrix} \mathbf{p^{new}} \\ \mathbf{\dot{e}^{new}} \end{bmatrix} = \begin{bmatrix} \mathbf{l^{new}} \\ \mathbf{k^{new}} \end{bmatrix} \tag{3.28}$$

$$\begin{bmatrix} \mathbf{C^{old}} & \mathbf{0} & \mathbf{S^{old}} & \mathbf{S^{PL}} \\ \mathbf{C^{EC}} & \mathbf{C^{ES}} & 0 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{p^{old}} \\ \mathbf{r^{ES}} \\ \mathbf{\dot{e}^{old}} \\ \mathbf{s\dot{o}c^{PL}} \end{bmatrix} = \begin{bmatrix} \mathbf{l^{old}} \\ \mathbf{0} \end{bmatrix} + \begin{bmatrix} \mathbf{k^{old}} \\ \mathbf{r^{inj}} \end{bmatrix} \tag{3.29}$$

3.4 Detailed Model of LES Considering PEVs' PL

Figure 3.2 demonstrates a LES equipped by a CHP unit, WG, AB, HS, and PEVs' PL. Input energy carriers are electricity, natural gas, and electric reserve of PL ($p^{in}_{\omega,t} = [w^{in}_{\omega,t} + w^{wind}_{\omega,t} \quad g^{in}_{\omega,t} \quad r^{PL}_{\omega,t}]$), while output energy services are electricity and heat ($l^{MED}_t = [W^{MED}_t \quad Q^{MED}_t \quad 0]$), and surplus energy services are electric power and reserve ($k^{inj}_{\omega,t} = [w^{inj}_{\omega,t} \quad 0 \quad r^{inj}_{\omega,t}]$). Equation 3.4, as shown at the top of next page, shows the energy hub model of LES considering its interaction with MEP and MED.

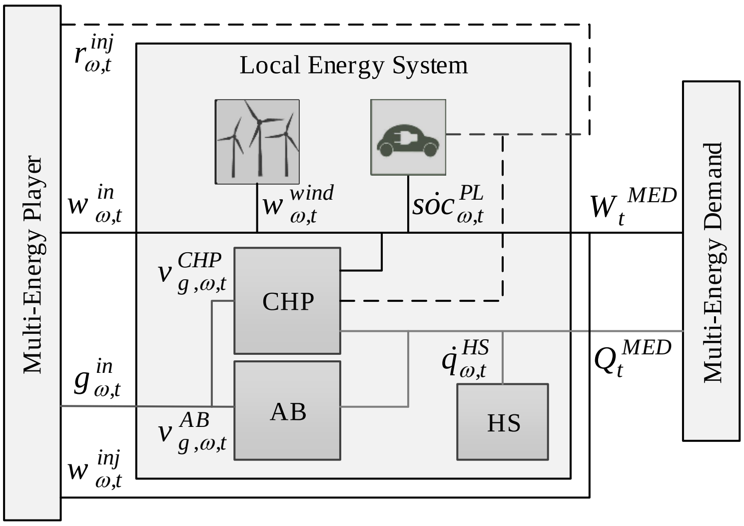

Figure 3.2: Local energy system schematic considering PEVs' PL.

$$
\begin{bmatrix}
0 & v^{CHP}_{g,\omega,t}\,\eta^{CHP}_e & 0 & 0 & 1/\eta^{PL}_e \\
0 & v^{CHP}_{g,\omega,t}\eta^{CHP}_h + v^{AB}_{g,\omega,t}\eta^{AB}_h & 0 & 1/\eta^{HS}_h & 0 \\
0 & (\overline{G}^{in} - v^{CHP}_{g,\omega,t}\,g^{in}_{\omega,t})/g^{in}_{\omega,t} & 1/\eta^{PL,dCha}_h & 0 & 0
\end{bmatrix}
\begin{bmatrix}
w^{in}_{\omega,t} + w^{wind}_{\omega,t} \\
g^{in}_{\omega,t} \\
r^{PL}_{\omega,t} \\
\dot{q}^{HS}_{\omega,t} \\
\dot{soc}^{PL}_{\omega,t}
\end{bmatrix}
=
\begin{bmatrix}
W^{MED}_t \\
Q^{MED}_t \\
0
\end{bmatrix}
+
\begin{bmatrix}
w^{inj}_{\omega,t} \\
0 \\
r^{inj}_{\omega,t}
\end{bmatrix}
\tag{3.30}
$$

Equations 3.31 and 3.32 show the efficiency of ES elements, i.e., PL and HS, to interact with LES.

$$\eta_e^{PL} = \begin{cases} \eta_e^{PL,Cha} & if\ \dot{soc}_{\omega,t}^{PL} \geq 0\ (Charge/Standby) \\ 1/\eta_e^{PL,dCha} & if\ \dot{soc}_{\omega,t}^{PL} < 0\ (Discharge) \end{cases} \tag{3.31}$$

$$\eta_e^{HS} = \begin{cases} \eta_h^{HS,Cha} & if\ \dot{q}_{\omega,t}^{HS} \geq 0\ (Charge/Standby) \\ 1/\eta_h^{HS,dCha} & if\ \dot{q}_{\omega,t}^{HS} < 0\ (Discharge) \end{cases} \tag{3.32}$$

3.5 Uncertainty Characterization

The traffic pattern of PEVs in PL is related to the uncertain behavior of PEV owners. Therefore, a stochastic approach is applied to model the characteristics of PEVs in PL, i.e., the number, total capacity, and SOC in each hour. Furthermore, the stochastic approach covers the uncertainty of WG. On this basis, two groups of scenarios are generated for PL and WG, and the PL operation is accomplished by considering these scenarios.

3.5.1 PEV's Uncertain Behavior in Parking Lot

The uncertainties of total capacity and SOC of PEVs at PL are modeled by a stochastic model. The capacity of PL is dependent on both the number and type of PEVs parked at the PL. In this paper, the PL refers to a parking structure that is located at a specific point. However, the generated scenarios are based on an average traffic behavior of car owners. In other words, it is assumed that the PL is an aggregation of all PLs that are geographically scattered over the study region. The PEV owner's travel patterns are extracted from [89]. To this end, it is assumed that PEV drivers will have a travel behavior similar to internal combustion engine vehicle drivers, traveling an average daily distance of 39.5 miles. This is employed to calculate the SOC of PEVs arriving to the PL.

On the other hand, the ES capacity of each PEV depends on the EV class. In [90], PEV batteries have been categorized to twenty four different classes. On this basis, the redundancy of the mentioned classes is considered as the probability distribution of the battery capacities in a market as in figure 3.3. According to the probability distribution of PEV classes and the probability of the number of PEVs at PL, the probable capacity of PEVs at PL is obtained as in Figure 3.4. SOC of PL relies on the daily driven distance of each PEV and the mentioned capacity of PEVs at PL. The probabilistic traveled distance is applied to calculate the SOC of PL.

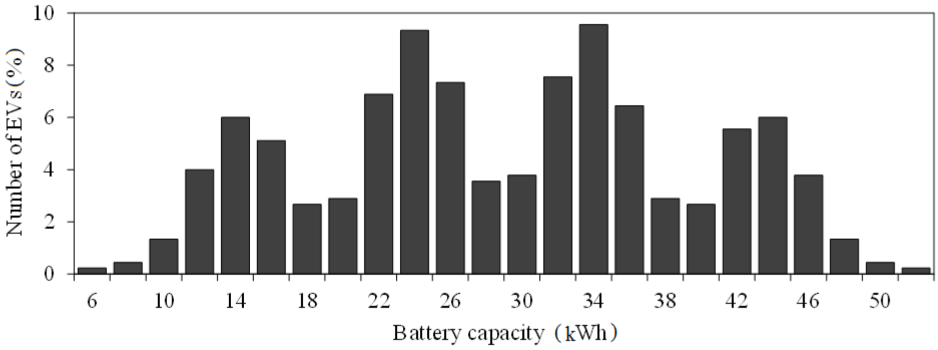

Figure 3.3: Probability distribution of battery capacity.

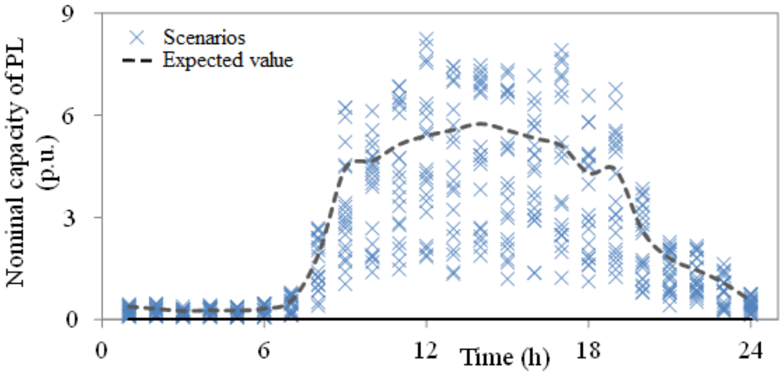

Figure 3.4: Hourly nominal capacity of EVs at PL.

Based on [91], the lognormal distribution function is utilized to generate the probabilistic daily distance. The daily traveled distance, M_d, can be formulated as 3.33 [92].

$$M_d = exp\left(ln(\mu_{md}^2/\sqrt{\mu_{md}^2+\sigma_{md}^2}\ ) + N.ln(\mu_{md}^2/\sqrt{\mu_{md}^2+\sigma_{md}^2}\ )\right) \tag{3.33}$$

where N is the standard normal random variable, and $\mu_m d$ and $\sigma_m d$ are the mean and standard deviation of M_d, being both calculated based on historical data [89]. According to [89], vehicles travel an average daily distance of 39.5 miles. On the other hand, an EV takes approximately 0.35 kWh to recharge for each mile traveling [89]. On this basis and according to the above mentioned description, the hourly SOC of PL is obtained as in figure 3.6.

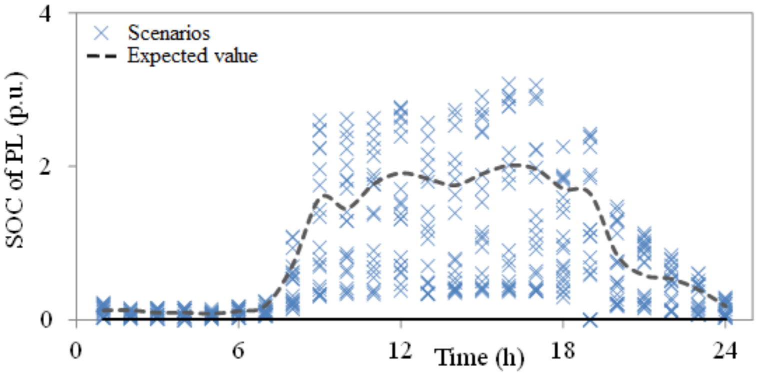

Figure 3.5: Hourly SOC of PL.

3.5.2 Wind Generation Uncertainty

Uncertainties of wind power are modeled to generate appropriate input scenarios for this chapter. Although accurate probability distribution function (PDF) of wind speed is nonstationary and no discernible actual PDF can be adjusted to it, yet most of the previous researches (see [93]) have used Weibull distribution in order to model wind speed. On this basis, the probability of each wind speed scenario can be calculated as follows:

$$prob_\omega = \int_{WS_\omega}^{WS_{\omega+1}} (k/c)(v/c)^{k-1} exp[-(v/c)^k]dv \tag{3.34}$$

where c > 0 and k > 0 are referred to as the scale and shape factors, respectively. WS_ω is the wind speed of the ωth scenario.

The wind power, P_{GW}, corresponding to a specific wind speed, WS_ω, can be obtained from (A.44). In (A.44), A, B, and C are constants that can be calculated according to [34]

$$P_{GW}=\begin{cases}0 & 0\le WS_\omega\le V_c \;\; or \;\; WS_\omega\ge V_{c0}\\ P_r(A+B*WS_\omega+C*WS_\omega^2) & V_c\le WS_\omega\le V_r\\ P_r & V_r\le WS_\omega\le V_{c0}\end{cases} \tag{3.35}$$

where V_c, V_{c0}, and V_{cr} represent cut-in speed, cut-out speed, and rated speed, respectively. According to the above mentioned descriptions, different scenarios are generated based on roulette wheel mechanism [94].

It should be noted that, although the higher number of scenarios produces a more accurate model to consider the uncertainties, it may yield an unmanageable optimization problem. Therefore, a scenario reduction technique is considered, using k-means clustering technique, resulting in a scenario tree with independent scenarios that is applied to the case studies.

Moreover, in this chapter, the swift current wind data are used to generate wind power scenarios [34]. On this basis, the generated scenarios are illustrated in figure **??**.

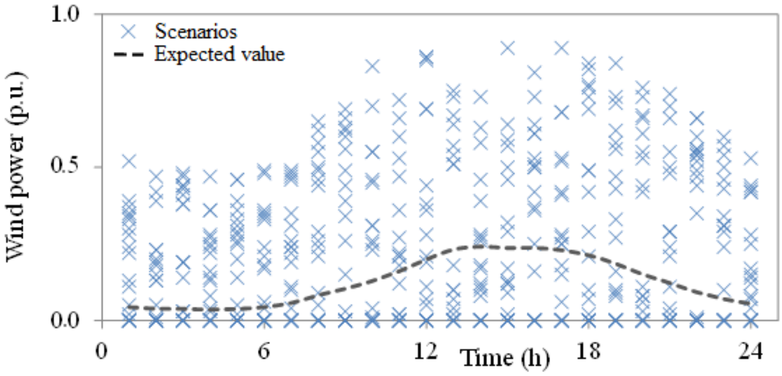

Figure 3.6: Wind power generation scenario.

3.6 PEVs' PL Operational Model

The SOC of PEVs in the PL is a tool for LES operator to maximize its profit. PL has interactions with MES as well as PEVs. It buys electric energy from MES for charging the PEVs' batteries that, on the other hand, is solely to the MES in peak hours, while PEV owners will also be charged for that. Moreover, PL participates in the reserve market, which motivates the increase of its SOC for achieving more benefit.

Equation 3.36 demonstrates that PL interaction with LES is equal to soc. Moreover, 3.37 represents the amount of this variable based on the level of SOC in two consequent time intervals and the impact of arrived and departed PEVs.

$$s\dot{o}c^{PL}_{\omega,t} = w^{PL,in}_{\omega,t} - w^{PL,out}_{\omega,t} \tag{3.36}$$

$$s\dot{o}c^{PL}_{\omega,t} = soc^{PL}_{\omega,t} - soc^{PL}_{\omega,t-1} + soc^{PL,ar}_{\omega,t} - soc^{PL,dep}_{\omega,t} \tag{3.37}$$

The following assumptions have been considered to formulate the impact of arrived and departed PEVs.

- If the SOC amount increases in each scenario in two consecutive time intervals, the increase will be equal to arriving PEVs' SOC to the system [3.38 and 3.39]
- If the SOC amount decreases in each scenario in two consecutive time intervals, the normalized reduction multiple PEVs' SOC in prior time will be equal to the departed PEVs' SOC from the system [3.40 and 3.41].
- In each hour and scenario, one of the departure or arrival conditions will be considered.

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \geq 0 \Rightarrow soc^{PL,ar}_{\omega,t} = soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \tag{3.38}$$

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \leq 0 \Rightarrow soc^{PL,ar}_{\omega,t} = 0 \tag{3.39}$$

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \geq 0 \Rightarrow soc^{PL,dep}_{\omega,t} = 0 \tag{3.40}$$

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \leq 0 \Rightarrow soc^{PL,ar}_{\omega,t} = ((soc^{PL,Sc}_{\omega,t-1} - soc^{PL,Sc}_{\omega,t})/soc^{PL,Sc}_{\omega,t-1})soc^{PL}_{\omega,t-1} \tag{3.41}$$

In addition, to determine the PL financial transaction with PEV owners, 3.42-3.45 calculated the SOC difference of PEVs' battery at departure time. Main assumptions are as follows.

- If the SOC of departed PEVs is more than the SOC reduction in two consecutive time intervals in each scenario, PL is selling energy to the PEVs [3.42 and 3.43].
- Otherwise, PL is buying energy from PEVs [3.44 and 3.45].
- In each hour and scenario, PL is conditioned by one of the mentioned terms.

$$if \quad soc^{PL,dep}_{\omega,t} \leq soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \Rightarrow soc^{PL,up}_{\omega,t} = 0 \tag{3.42}$$

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \leq soc^{PL,dep}_{\omega,t} \Rightarrow soc^{PL,up}_{\omega,t} = soc^{PL,dep}_{\omega,t} - (soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1}) \tag{3.43}$$

$$if \quad soc^{PL,dep}_{\omega,t} \leq soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \Rightarrow soc^{PL,down}_{\omega,t} = soc^{PL,Sc}_{\omega,t} - (soc^{PL,Sc}_{\omega,t-1} - soc^{PL,dep}_{\omega,t}) \tag{3.44}$$

$$if \quad soc^{PL,Sc}_{\omega,t} - soc^{PL,Sc}_{\omega,t-1} \leq soc^{PL,dep}_{\omega,t} \Rightarrow soc^{PL,down}_{\omega,t} = 0 \tag{3.45}$$

Equations 3.46-3.48 demonstrate the PLs capability to interact with LES, which is related to the number of PEVs in each hour and PL facilities for charging/discharging of PEVs' battery. The amount of injected energy to the MES is restricted by the participation factor ($\phi^{PL}_{e,t}$) of PEVs in V2G mode. Furthermore, the PLs capability of participating in the reserve service is limited by the free capacity of PL interconnector system with MES and the level of PEVs participation ($\phi^{PL}_{r,t}$) in ancillary service. The participation factors in both reserve and energy cases can be determined based on the willingness of PEVs owners to share their PEVs' capability with the PL owner, instead of using parking facilities and receiving incentives

$$w^{PL,in}_{\omega,t} \leq \gamma^{PL}_{\omega,t} = \Gamma^{PEV} N^{PL,Sc}_{\omega,t} \tag{3.46}$$

$$w^{PL,out}_{\omega,t} \leq min(\gamma^{PL}_{\omega,t}, \phi^{PL}_{e,t} soc^{PL}_{\omega,t}) \tag{3.47}$$

$$r^{PL}_{\omega,t} \leq min(\phi^{PL}_{r,t} soc^{PL}_{\omega,t} - l^{PL,out}_{\omega,t}, \gamma^{PL}_{\omega,t} - l^{PL,out}_{\omega,t}, 0) \tag{3.48}$$

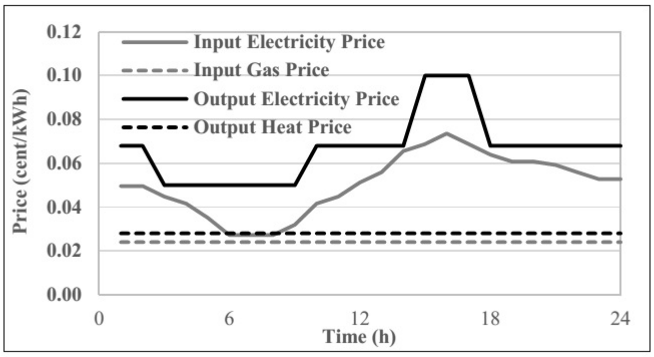

Figure 3.7: Input and output energy price of LES.

SOC of PEVs should be kept at the minimum and maximum bounds of its operation condition. Therefore, 3.49 and 3.50 determine the minimum and maximum amount of PLs SOC based on the number of PEVs in the parking and safe criteria of PEVs' battery operation in each hour. Moreover, 3.51 restricts the amount of PLs SOC in its minimum and maximum value, being less than the total PL capacity.

$$\underline{SOC}^{PL}_{\omega,t} = \underline{SOC}^{EV} N^{PL,Sc}_{\omega,t} \tag{3.49}$$

$$\overline{SOC}^{PL}_{\omega,t} = \overline{SOC}^{EV} N^{PL,Sc}_{\omega,t} \tag{3.50}$$

$$\underline{SOC}^{PL}_{\omega,t} \leq SOC^{PL}_{\omega,t} \leq \overline{SOC}^{PL}_{\omega,t} \leq C^{PL}_{\omega,t} \tag{3.51}$$

3.7 Numerical Study

3.7.1 Input Data Characterization

In the proposed model, the LES is equipped with CHP unit, AB, WG, HS, and PL. Data of the energy and reserve prices for input of LES have been obtained from hourly data of the Spanish electricity market in July 2010 [27]. The output prices and MEDs consumption are obtained from [28] with some modifications.

The LES elements characterization and energy price signals are represented in Table 3.1 and figure 3.7, respectively.

Table 3.1: Data of Local Energy System Elements.

Elements		**Value**
CHP	Output Electricity	250 kW
	Output Heat	300 kW
	η_h^{CHP}	0.36
	η_e^{CHP}	0.45
	FOR^{CHP}	0.02
	$\underline{\Phi}^{CHP}, \overline{\Phi}^{CHP}$	1, 2
AB	Output Heat	600 kW
	η_h^{AB}	0.85
HS	Energy Capacity	200 kWh
	Γ_h^{HS}	100 kW
	$\eta_h^{HS,Cha}$, $\eta_h^{HS,dCha}$	0.9, 0.9
PL	Γ_e^{PL}	11 kW/EV
	$\eta_e^{PL,Cha}$, $\eta_e^{PL,dCha}$	0.9, 0.9
	FOR^{PL}	0.02
	$\phi_{e,t}^{PL}, \phi_{r,t}^{PL}$	0.4,0.7

3.7.2 Case Studies

Three case studies are assumed for assessing the proficiency of the proposed model and the behavior of PL in LES. Case I is considered to demonstrate LES operational behavior without PL interaction. In case II, the PL is added to the system to investigate the behavior of each LES elements in the presence of PL as a source of operational flexibility for the LS operator. Moreover, case III compares the behavior of LES operator with and without participating in the reserve market as another source of operational flexibility for LES operator.

1) Case I: The operation of LES is considered without interaction with PL. Figure 3.8 demonstrates the share of LES, CHP, and WG in MEDs electricity demand. Moreover, figure 3.9 shows the share of AB, CHP, and HS in MEDs heat demand. The CHP unit generates heat and electricity based on its economic considerations and between the hours 5, 11–14, and 18–22, while the MED consumes both electricity and heat and the electricity price is high. Although in hours 2, 10, 15–17, 23, and 24 there is no heat demand, due to high electricity price the CHP generates the electricity need of MED and surplus heat stored in HS. Moreover, AB and HS compensate the shortage of heat demand when more heat production of CHP is not beneficial. The surplus heat energy stored in HS is delivered to the LES in heat demand hours.

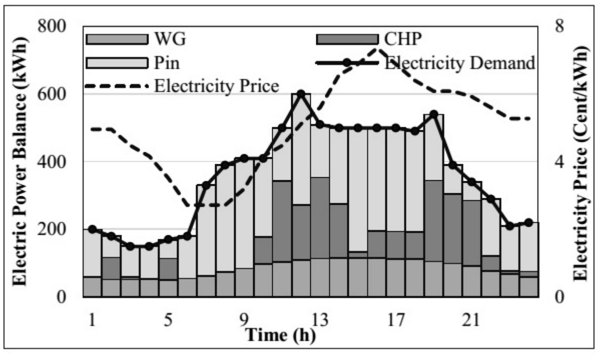

Figure 3.8: Share of each LES energy elements in output electricity in Case I.

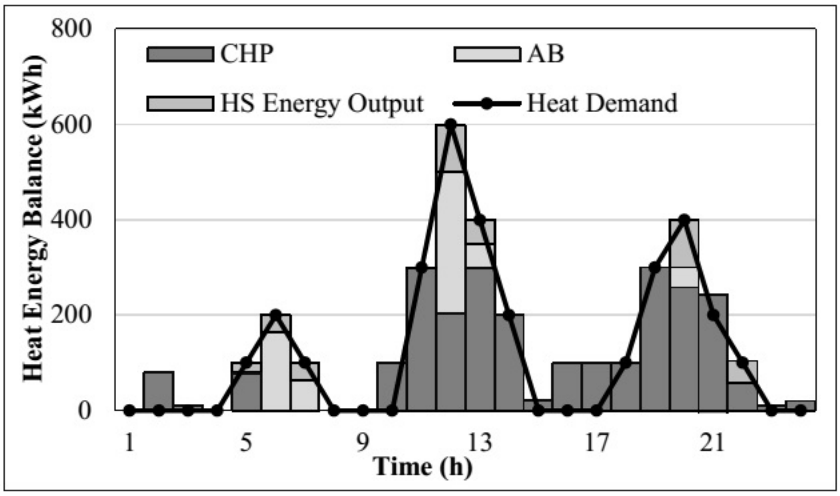

Figure 3.9: Share of LES energy elements in output heat in Case I.

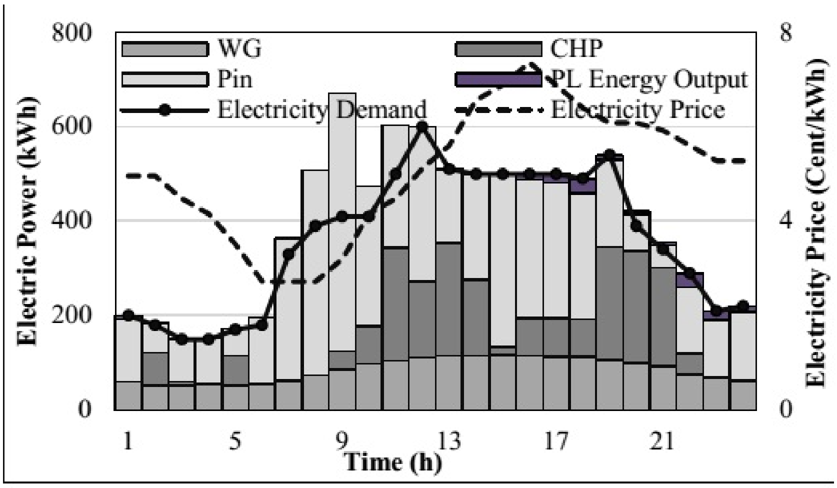

Figure 3.10: Share of each LES energy elements in output electricity in Case II.

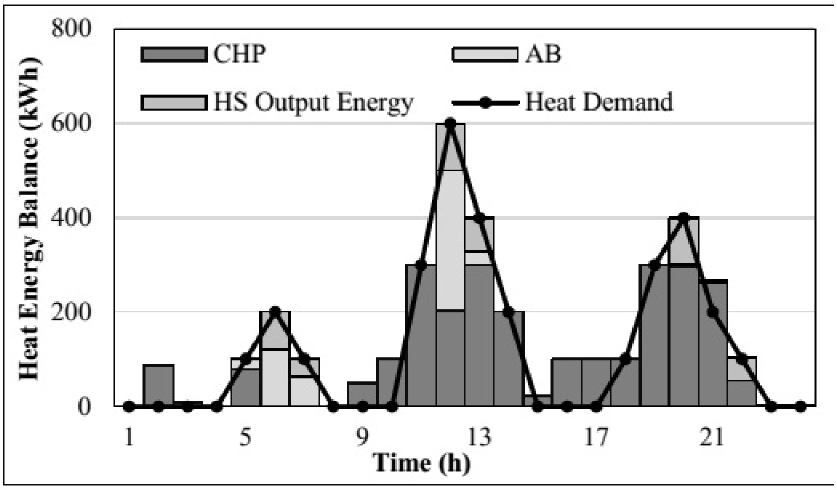

Figure 3.11: Share of LES energy elements in output heat in Case II.

2) Case II: The PL is considered as one of the LES elements and it interacts with both electric energy and reserve services. Figures 3.10 and 3.11 depict the share of each LES elements in electricity and heat energy balance of LES, respectively. Between hours 7–12, the PL receives energy to charge its PEVs' batteries. Moreover, in hours 16–24, the PL injects about 154 kWh to the LES while the electricity price is high.

Furthermore, figure 3.12 shows the share of CHP and PL in the output of reserve service. As it is shown, the CHP unit prefers to participate in the electric energy market rather than the reserve market and introduces only its vacant capacity in the reserve market. On the contrary, higher share of PLs profit is for its participation in

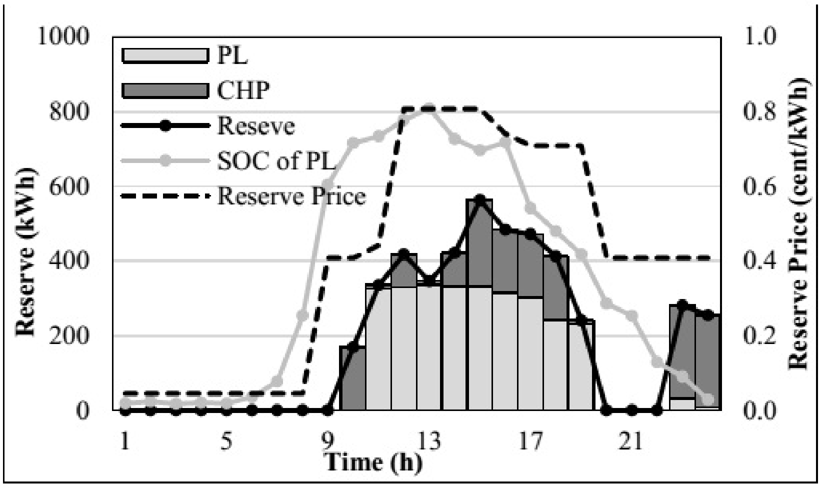

Figure 3.12: CHP and PL share in reserve service in Case II.

the reserve market. Between hours 11–19 when reserve price is higher, PL delivers reserve service to the system. At other hours, because of lower reserve price and the risk of incurring penalty in reserve supplement, the PL does not deliver reserve service.

3) Case III: The interaction of PL with LES is considered but the capability of LES to deliver reserve service is denied. Figures 3.13 and 3.14 demonstrate electricity and heat balance in LES, respectively. It is shown that through hours 7–12 the PL has the same behavior as in case II, but in this case the PL injects more electricity to the LES (418 kWh) in hours 15–19 because the LES operator is not capable to participate in the reserve market; hence, it prefers to enhance its energy trade to maximize profit.

3.7.3 Discussion

The MES concept introduces an operational flexibility to the system operators from both decision making and technical points of view. In the proposed model, participating in reserve market and adding PL as an ES element are considered as resources of operational flexibility. Participating in the reserve market, which is originated from a long-term policy making structure, gives a degree of freedom to the LES operator for maximizing its profit. Furthermore, installing new energy elements (e.g., ESs and ECs) in the long-term facilitates the enhancement of system

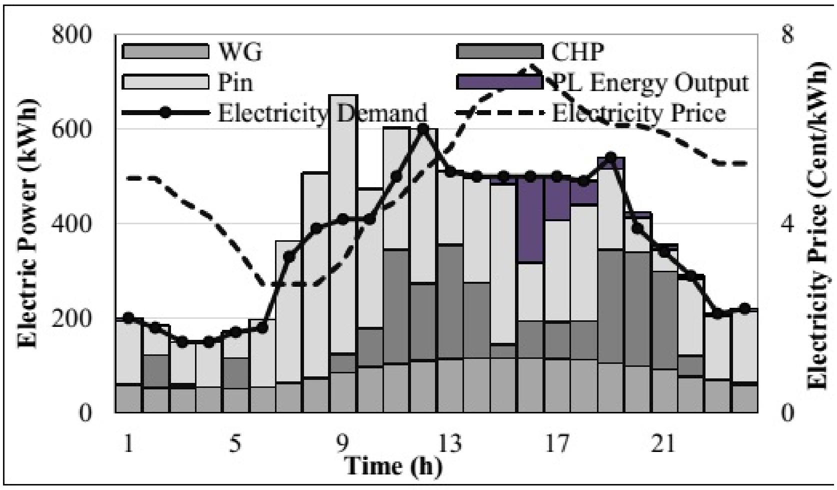

Figure 3.13: Share of each LES energy elements in output electricity in Case III.

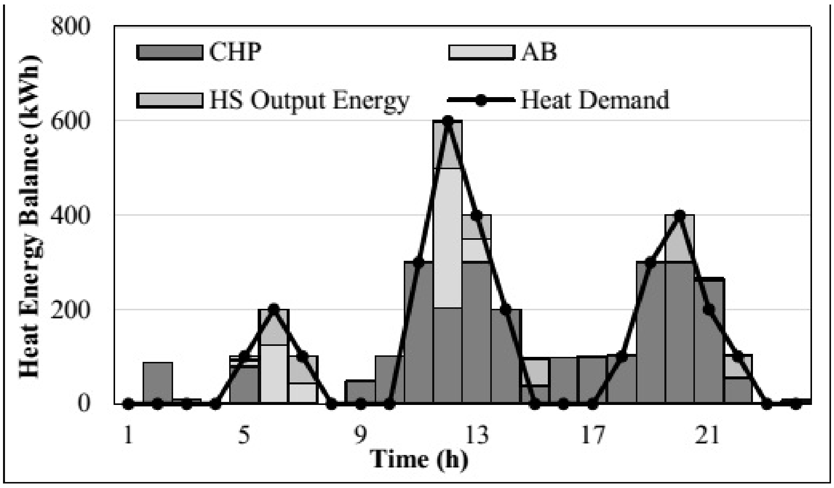

Figure 3.14: Share of LES energy elements in output heat in Case III.

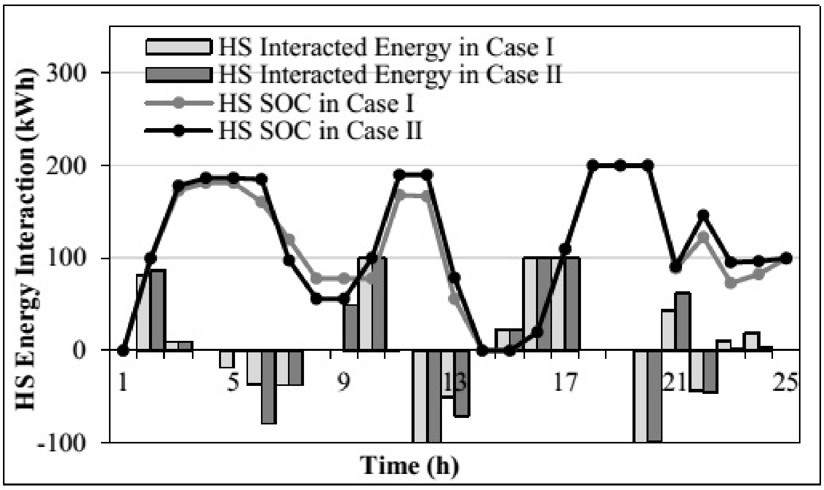

Figure 3.15: Operation pattern of HS in cases I and II.

operator's flexibility to choose between carriers and time intervals in the operation time horizon. In this regard, the PL behaves like storage with uncertain behavior in LES environment. Thus, it changes the operational pattern of LES operator. Figure 3.15 compares the operation of HS in cases I and II as the indicator of change in LES operational flexibility in the presence of PL. It shows that in case II, where the LES has interaction with PL, the HS is utilized more and its charge and discharge are deeper. This means that by implementing new energy elements the operation of the other elements will be affected. Based on this, integrated models are needed to cover the mentioned internal interactions. Moreover, LES profit has increased from 306 to 333 , as shown in Table 3.2, which also confirms the deduction that increasing the flexibility of the system will help in delivering energy services while assuring a higher system profit.

Table 3.2: Financial Transaction of LES in Three Cases.

	Case I	**Case II**	**Case III**
Electricity Cost ()	238	255	248
Natural Gas Cost ()	149	151	152
Reserve Profit ()	6	19	0
PL Profit ()	0	32	28
Selling to MED ()	688	688	688
Total ()	306	333	316

Moreover for determining the role of reserve market in the operational flexibility of LES, figure 3.16 depicts the PL behavior in cases II and III. As it can be seen, in case II when PL delivers reserve service its output electric energy is less than when it

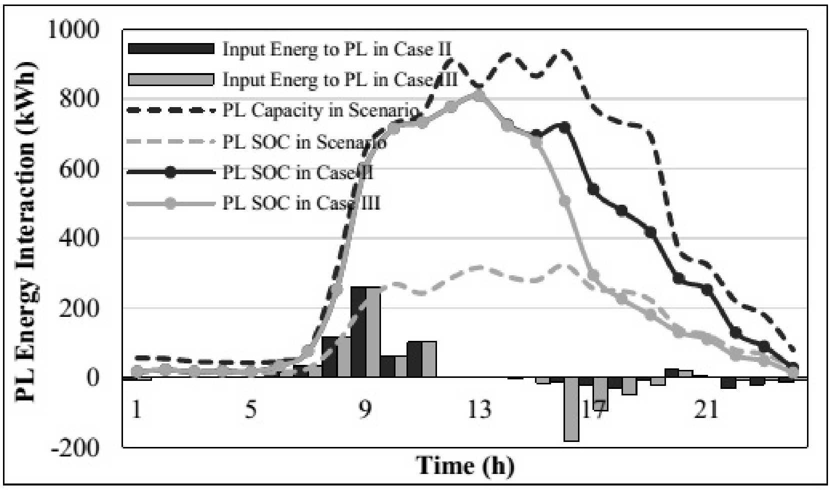

Figure 3.16: Operation pattern of PL in cases II and III.

only participates in the electric energy interaction. The reason is that the PL prefers to charge the PEVs' battery and increase its SOC to deliver reserve service in the middle of a period and sell the charged energy to the PEVs' owners at the end of the period. Table 3.2 demonstrates the total amount and each term in the objective function. It can be seen that in case II the operator has the maximum profit while it has both sources of flexibility in the system. Moreover, part of this maximum profit in case II is due to selling more SOC to the PEVs ($32 - 28 = 4$). Case I shows that the profit of micro-MES participation in reserve market is 6 and case III determines that the profit of LES in the presence of PL and from participating in the energy market is 16 . Moreover, utilizing both of these flexibilities added 33 to micro-MES profit. The difference between these amounts are about 0.3%, which shows that the two flexibility resources have a cross-impact and utilizing both of them simultaneously increases each individual impact.

3.8 Chapter Summary

This chapter has modeled the PL as an energy element in MES. The proposed model considers PL as the aggregation of PEVs' batteries that reflects the uncertain behavior of PEVs' owners in arriving to and departing from PL. For assessing the realistic PL interaction with MES, the reserve service was considered as an output energy service. The energy hub model has been modified to cover all of these considerations. The numerical results have shown the role of PL in changing the operational behavior of other MESs elements and enhancing MES operational flexibility to deliver energy demand. Moreover, considering the reserve service in the modeling has highlighted the behavior of PL as a flexible load, rather than its storage nature, which increases profit from both charging the PEVs' batteries and participating in reserve supplement.

Chapter 4

Modeling Multi-Energy demand dependency in LES

In a multi-energy system (MES), there are different types of dependencies among the energy carriers. Internal dependencies refer to possible changes in the energy source in the presence of energy converters and storage, and are managed by the system operator through the control strategies applied to the equipment. External dependencies (EDs) are due to the choice of the energy supply according to customer preferences when alternative solutions are available. This chapter introduces a new model of EDs within a multi-generation representation based on energy hubs. EDs are addressed through a stochastic model in order to take into account the possible uncertainty in the customers' decisions. This model is then used to introduce carrier-based demand response (DR) in which the user participates in DR programs aimed at promoting the shifting among different energy sources by preserving the service provided to the end users. The results obtained from the new model in deterministic and stochastic cases indicate the appropriateness and usefulness of the proposed approach.

4.1 Dependency Definition

In a MES, the dependencies can be divided in two main categories: 1) internal dependencies; and 2) external dependencies (EDs).

The internal dependencies refer to the relations between input and output energy carriers due to the presence of energy converters existing in the MES and controlled by the system operator (for example, deciding the energy flows among multiple equipment belonging to a MES, on the basis of a specified control strategy or optimization objective [35], [33]).

Conversely, the EDs are mainly due to actions not depending on the network operator, which may have effects on the way the MED is served. These actions generally depend on the user's preferences triggered by DR programs and incentives established by the regulator. The considerations of the EDs also depend on the penetration level of the distributed energy converters located at the user's side and directly activated by the customers for changing the energy supply (e.g., electrical and gas boilers for hot water production, and local management of storage).

The framework representing the relations of various elements in the MES and the position of internal dependencies and EDs is shown in figure 4.1. As the dependent demand causes an ED in the system, it will affect the conventional models used for the MES. Two main references that have focused on modeling the dependencies are [32] and [1]. In these references, the dependency between carriers is considered through the coupling matrix.

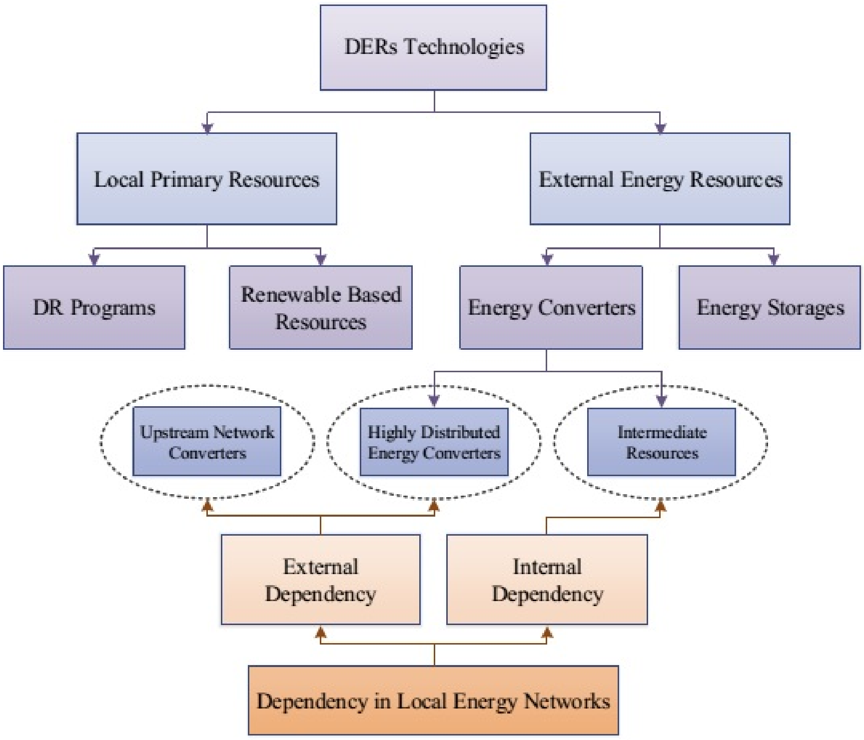

Figure 4.1: Structure of DER supply and related dependencies in serving MED.

Furthermore, Kienzle et al. [8] addressed the model of the external time dependency arising by modeling the stored heat demand as DR in a residential area. However, the survey of the literature approaches shows that a structured view of the dependencies among the energy carriers, taking into account the role of the user and the related preferences, has not been provided yet. Hence, in the proposed model, the ED on the demand side is modeled as a specific module in the LES, which has not been tested in previous studies, posing a new contribution. In addition, the stochastic nature of consumer preferences is addressed. This will bring higher levels of flexibility to the energy usage in the network, while reducing operation costs.

4.2 Modified Comprehensive LES Model

Energy systems have a multi-layer nature. A possible representation with three main layers is indicated in figure 4.2, namely, MEP (referring to external energy systems and networks), LES (i.e., the local system under analysis), and MED.

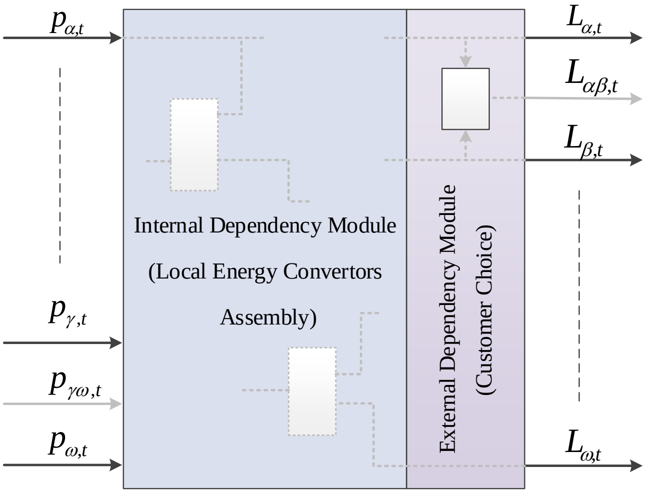

Figure 4.2: Energy system comprehensive module considering internal and external dependencies.

The energy system analysis is carried out by assuming that the services requested by the user and the associated MED are known. Looking at the LES equipment, two main elements exist in the energy system model: 1) energy converters; and 2) energy storages. In this section, the matrix model for these elements is presented, highlighting the effects of the possible interdependencies among the energy carriers. The time scale used for the representation depends on the averaging time interval with which the data are available. Without loss of generality, the subscript t is used here to scan the time intervals.

Thereby, this model is efficient both on the operation timescale, provided that appropriate control or DR signals are available in a relatively short term (from minutes to hours) to change the equipment set point (thus affecting the internal dependencies) or to induce changes in the customers' preferences as EDs, and in long-term planning of local energy networks. The classical model encompasses the presence of the internal dependencies referring to the energy CS among different equipment, in which the decision variables (e.g., the dispatch factors indicated in [32]), represent degrees of freedom to determine the energy flows in the multienergy system and can be set up as a result of optimization procedures run by considering specific objective functions [32], [95]. However, this model formulation does not include the representation of the customer choice affecting the energy carriers' usage. This representation is incorporated here in the ED module highlighted previously in figure 4.2.

The proposed extension of the model shows that, besides consuming a certain amount of each energy carrier at each time interval ($L_{\alpha t}$, $L_{\beta t}$, etc.), the MED has the ability to receive a defined amount of energy ($L_{\alpha\beta t}$) from different carriers to supply the required service. The weighted energy contributions depending on the customer preferences in the ED module are equivalent to the dispatch factors considered in the model representing the internal dependencies.

Dependency between outputs is added to the demand vector through one or more additional entries, which increase the number of rows of the coupling matrix 4.1. It should be noted that these added lines do not represent actual outputs, but virtually illustrate the dependency in output.

$$\begin{bmatrix} L_{\alpha t} \\ L_{\beta t} \\ \vdots \\ L_{\omega t} \\ L_{\alpha\beta t} \end{bmatrix} = \begin{bmatrix} C_{\alpha\alpha} & \dots & C_{\alpha\omega} \\ C_{\beta\alpha} & \dots & C_{\beta\omega} \\ \vdots & \ddots & \vdots \\ C_{\omega\alpha} & \dots & C_{\omega\omega} \\ C_{\alpha\beta\alpha} & \dots & C_{\alpha\beta\omega} \end{bmatrix} \begin{bmatrix} p_{\alpha t} \\ p_{\beta t} \\ \vdots \\ p_{\omega t} \end{bmatrix} \tag{4.1}$$

Hence, the output vector $\mathbf{l}$ in the proposed model (column vector containing the terms $L_{\alpha t}$, $L_{\beta t}$, etc.) can be divided into two sections as in 4.2, with rows indicating independent output carriers ($\mathbf{l_I}$) and rows introducing dependency in the output ($\mathbf{l_D}$). The same approach can be performed on the coupling matrix. Therefore, the matrix model will have new rows that make it different with respect to the one used in [42] and [45].

$$\begin{bmatrix}\mathbf{l_D}\end{bmatrix} = \begin{bmatrix}\mathbf{l_I}\\ \mathbf{l_D}\end{bmatrix} = \begin{bmatrix}\mathbf{C_I}\\ \mathbf{C_D}\end{bmatrix}\begin{bmatrix}\mathbf{p}\end{bmatrix} \tag{4.2}$$

where

$\mathbf{C_I}$	traditional coupling matrix that states the conversion of independent inputs into independent outputs;
$\mathbf{C_D}$	matrix showing the share of the independent inputs in providing dependent demand;
$\mathbf{p}$	column vector containing the input variables.

By decomposing the storage coupling matrix $\mathbf{S}$ into its components $\mathbf{S_I}$, showing changes of independent output versus changes in the stored energy, and $\mathbf{S_D}$, showing changes of dependent output versus changes in the stored energy, the matrix formulation becomes as 4.3.

$$\begin{bmatrix}\mathbf{l_I}\\ \mathbf{l_D}\end{bmatrix} = \begin{bmatrix}\mathbf{C_I} & \mathbf{S_I}\\ \mathbf{C_D} & \mathbf{S_D}\end{bmatrix}\begin{bmatrix}\mathbf{p_n}\\ \dot{\mathbf{e}}_\mathbf{s}\end{bmatrix} \tag{4.3}$$

4.3 Local Energy System Stochastic Operational Model

In order to show an application of the proposed model, a typical local network model is shown in figure 4.3, with CHP unit, AB, and HS.

The input carriers of the system are electricity and gas, while the output carriers are electricity, gas, and heat. The ED between gas and electricity carriers in this network is considered through the demand dependency module ED in the output (with output variable Leg,t). The EDs due to the behavior of the consumers are not deterministic; therefore, the related uncertain variables are considered in a

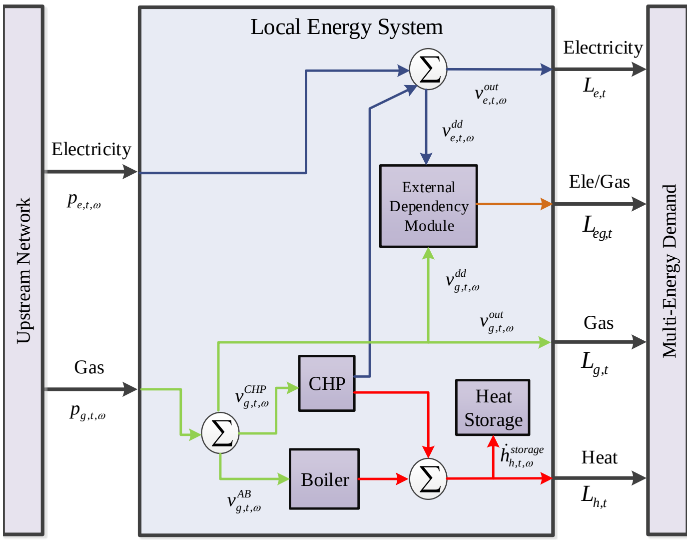

Figure 4.3: A typical local energy network model considering the energy carriers dependency.

scenario-based stochastic model, in which the subscript s represents the scenarios. The typical scenarios considered are the CS indicated in Section 7.1 when no DR program is defined, and the CBDR scenarios considering the shifting between energy carriers in order to maintain the customers' satisfaction through the definition of DR programs. It is assumed that some customers agree that their demand would be participating in this type of DR. CS is based on the user's decision on which multi-energy carrier has to be used for the part of dependent demand that does not participate in CBDR programs, while the remaining part of the dependent demand is available to contribute to CBDR.

The considerations on uncertainty and the details of the scenarios are described in the next section. The energy dispatch between the various elements is described by using the weighted energy contribution variables v, for both internal and EDs. The links among the weighted energy contribution variables are indicated hereafter. Based on the proposed model in the previous section, the mathematical model of this network is shown in 4.4.

$$\begin{bmatrix} v_{e,\omega,t}^{out} & v_{g,\omega,t}^{CHP}\eta_e^{CHP}v_{e,\omega,t}^{out} & 0 \\ 0 & v_{g,\omega,t}^{CHP}\eta_h^{CHP} + v_{g,\omega,t}^{AB}\eta_h^{AB} & 1/\eta_h^r \\ 0 & v_{g,\omega,t}^{out} & 0 \\ v_{e,\omega,t}^{dd} & v_{g,\omega,t}^{dd} + v_{e,\omega,t}^{dd}v_{g,\omega,t}^{CHP}\eta_e^{CHP} & 0 \end{bmatrix} \begin{bmatrix} w_{\omega,t}^{in} \\ g_{\omega,t}^{in} \\ \dot{q}_{\omega,t}^{HS} \end{bmatrix} = \begin{bmatrix} L_{e,t} \\ L_{h,t} \\ L_{g,t} \\ L_{eg,t} \end{bmatrix} \tag{4.4}$$

It should be noted that in this chapter the model is studied in steady state, namely, the time step of analysis is considered to be sufficiently long to assume that all the equipment (also the slower thermal elements on the demand side) have concluded their transient period and have reached their steady state. As a result, the dynamics on the demand side can be neglected.

The local energy network is assumed to consist of small residential smart buildings, in which indicatively the minimum time step for analyzing successive steady-state conditions can be of the order of minutes. In any case, the time step used for the calculations in this chapter is longer (hours), so the representation of the equipment dynamics is not needed.

4.3.1 Objective Function

The objective function in operating this system is to minimize the costs of providing the required amount of gas energy input $g_{\omega,t}$ and electrical energy input $w_{\omega,t}$, taking into account the costs per unit of energy $\Pi_{e,t}$ and $\Pi_{g,t}$ for electricity and gas, respectively.

This model has been formulated to obtain the total expected cost for various scenarios of dependency in the system.

$$Minimize\left\{ f(x) = \sum_{\omega} \rho_{\omega} \sum_{\alpha} \sum_{t} \left[w_{\omega,t}\Pi_{e,t} + g_{\omega,t}\Pi_{g,t} \right] \right\} \tag{4.5}$$

with

$$\rho_s = \{\rho_s^{CB}, \rho_s^{CS}\} \tag{4.6}$$

where ρ_s^{CB} and ρ_s^{CS} are respectively the probabilities of being in the CBDR or in the CS scenarios. The details of the scenarios are explained in the appendix.

4.3.2 Model of External Dependency

As shown in the proposed model, the EDs are modeled in a block added to the rest of the LES model. In fact, this block is the interface between the LES and the output demand. However, in the proposed model, the dependency that actually happens on the demand side is modeled as a part of the LES. The block is added as a module in the model (figure 4.3). It should be noted that this module does not give a physical outcome, but it helps the operator of a MES to have an insight from possible customers' choice of carriers. In a real network, this module can have outputs such as data or information signals that are sent to the operator 24 h before the operation day. Nevertheless, in the proposed model, the mathematical model for investigating the compatibility of the model is presented. Based on these explanations, the dependency module demonstrates that part of the MED can utilize both electricity and gas carriers to provide the required service. In order to deal with the dependency between the carriers in the system model, two weighted energy contribution variables are used, namely, $v^{dd}_{e,\omega,t}$ and $v^{dd}_{g,\omega,t}$, stating the share of dependent energy demand in the output of each carrier (electricity and gas, respectively).

$$f\left(v^{dd}_{e,\omega,t}, v^{dd}_{g,\omega,t}\right) = L_{eg,t} \tag{4.7}$$

In 4.7, it is shown that the output dependent demand is a function of the variables of the two carriers (electricity and gas). The ED variables illustrate the dependent demand's share in usage of each carrier. Thus, it is necessary to balance them with some coefficients and then exploit them in the model. The following new weighted energy contribution variables in the output show the share of each carrier in demand provision:

$$v^{dd,n}_{e,\omega,t} = \left(\frac{w^{in}_{\omega,t} + g^{in}_{\omega,t} v^{CHP}_{g,\omega,t} \eta^{CHP}_{e}}{L_{eg,t}}\right) v^{dd}_{e,\omega,t} \tag{4.8}$$

$$v^{dd,n}_{g,\omega,t} = \left(\frac{w^{in}_{\omega,t}}{L_{eg,t}}\right) v^{dd}_{g,\omega,t} \tag{4.9}$$

As it is shown in 4.8 and 4.9, a new variable is defined to determine the share of dependent demand from electricity and gas, respectively. These equations show the share of dependent demand from the total input energy carriers. In other words, $v^{dd,n}_{e,\omega,t}$ shows what amount of dependent demand is served by electricity. The same can be interpreted for $v^{dd,n}_{g,\omega,t}$. Besides, these new variables are used to avoid the multiplication of weighted energy contributions and make the problem linear with respect to the decision variables.

Furthermore, it is clear that there is some equipment that enables the possibility of dependent demand. However, the equipment that has shares on energy contribution of the EDs is not ideal, and may waste some part of energy through the energy conversion process. Therefore, 4.10 represents the limit on the amount of weighted energy contribution variables depending on this block. This will ensure that the amount of energy that is assigned to each carrier is obtainable by the related equipment.

$$v^{dd,n}_{e,\omega,t} + v^{dd,n}_{g,\omega,t} \geq 1 \tag{4.10}$$

4.4 Uncertainty Characterization of internal and external dependency

The consumers' behavior for utilizing the mentioned dependencies is uncertain from the operator's point of view. Therefore, a scenario-based approach is adopted to characterize this behavior. This section describes the model of the uncertainties on CBDR and energy carriers share.

4.4.1 Uncertainty of Carrier-Based Demand Response

Let us assume that the LES operator can send signals at each hour to its consumers to inform them on the desirable energy dispatch. The consumers can respond to this request based on economic and social behavior. One of the main stimuli that motivate consumers to participate in CBDR programs is the presence of incentives that can be based on price signals. Some reports (see [96], [97]) have focused on modeling the customers' response during a DR event and obtaining the DR baseline error/accuracy. Customers' response uncertainty refers to the percentage of consumers who participate in CBDR programs. In other words, consumers' CBDR acceptance is the main source of uncertainty considered in the ED modeling.

In this thesis, a scenario-based approach is utilized to investigate the effect of the customers' response uncertainty on the operator's behavior. Another important uncertainty regards the consumers who do not participate in CBDR programs, thus their demand is individually controlled, contributing to the terms referring to the internal dependency. This uncertainty represents the probabilistic nature of consumers' behavior to select the carriers for supplying their own demand (figure 3.10).Equations 4.11–4.16 represent the share of each carrier for providing CBDR and individually controlled demand.

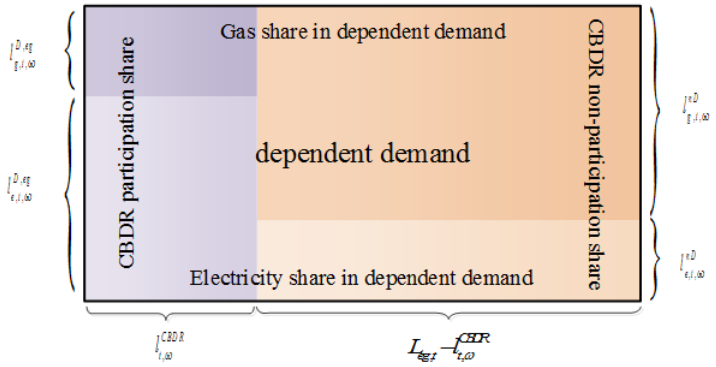

Figure 4.4: Share of demand participation variables in dependent demand.

$$l^{CB}_{eg,\omega,t} = L_{eg,t} v^{CB}_{\omega,t} \tag{4.11}$$

where $v^{CB}_{\omega,t}$ represents the variable indicating the customers that agree to participate in CBDR. Hence, $l^{CB}_{eg,\omega,t}$ determines the part of dependent demand that takes part in CBDR. The share of electricity and gas demand from total dependent demand is expressed as:

$$l^{CB}_{eg,\omega,t} v^{dd,n}_{e,\omega,t} = l^{CB}_{e,\omega,t} \tag{4.12}$$

$$l^{CB}_{eg,\omega,t} v^{dd,n}_{g,\omega,t} = l^{CB}_{g,\omega,t} \tag{4.13}$$

The choice of the customers who do not participate in CBDR from electricity and gas (that is, the users with CS dependent demand) is represented in the following equations, the variables $v^{CS}_{e,\omega,t}$ and $v^{CS}_{g,\omega,t}$ represent the share of electricity and gas, respectively.

$$\left(L_{eg,t} - l^{CB}_{eg,\omega,t} v^{CS}_{e,\omega,t}\right) = l^{CS}_{e,\omega,t} \tag{4.14}$$

$$\left(L_{eg,t} - l^{CB}_{eg,\omega,t} v^{CS}_{g,\omega,t}\right) = l^{CS}_{g,\omega,t} \tag{4.15}$$

$$v^{CS}_{e,\omega,t} + v^{CS}_{g,\omega,t} \geq 1 \tag{4.16}$$

In addition, the amount of dependent demand in the study (demand dependency percentage) is calculated through the following equation:

$$dd\% = \frac{L_{eg,t}}{\overline{L}_{eg,t}} \tag{4.17}$$

4.4.2 Modeling the Uncertainties of CBDR and Carrier Share

The model of the LES should estimate the uncertain parameters of probabilistic consumers' behavior by past statistics data. To create appropriate scenarios to model the mentioned uncertainties, several methods based on time-series (see [98]), artificial intelligence and evolutionary algorithms (see [99]) can be utilized.

In this thesis, the uncertainties are modeled as multiple different scenarios. Then, a scenario-based stochastic programming approach is employed to handle uncertainties. The scenario-based stochastic programming is an efficient tool to find optimal decisions in problems involving uncertainty. When it comes to make decisions under uncertainty using stochastic programming, the building of scenario sets that properly represent the uncertain input parameters constitutes a preliminary task of utmost importance. In reality, the optimal decisions derived from stochastic programming models may be indeed remarkably sensitive to the scenario characteristics of uncertain data. For this reason, a large number of researches have been accomplished to design efficient scenario generation methods. A brief description of the most relevant methods is presented in [100].

However, the generation of a huge number of scenarios may render the underlying optimization problem intractable. Therefore, it is necessary to consider a limited subset of scenarios without losing the generality of the original set. Scenario reduction techniques can reduce the number of scenarios effectively [101], [102]. The probabilistic behavior of customers has caused the operator to face plenty of uncertainties in order to participate effectively in the market. Each customer behaves differently because of social and economic concerns. Therefore, each individual behavior will be different from others. In the proposed model, two sets of uncertainty are considered, regarding the customers' behavior. The first set is the uncertainty of customers' response to participate in a CBDR program, and the second set is the uncertainty of selecting the different carriers by the customers. In order to generate scenarios with the mentioned uncertain variables, the normal distribution has been utilized, with PDF

$$f(x,\mu,\sigma) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{4.18}$$

where μ and σ represent the mean value and the standard deviation, respectively. In other words, it is assumed that the uncertain variables have normal deviations around their mean values. On this basis, different realizations of CBDR and CS are independently modeled by employing a scenario generation process based on roulette wheel mechanism [52]. For the sake of fair comparison, it is assumed that μ is equal to its amount in the deterministic case and different values of σ have been considered.

4.5 Numerical Results

For assessing the effectiveness of the proposed model, numerical results have been developed. As the internal dependency has been investigated in prior researches (see [34] and [33]), the numerical results presented here focus on the EDs. The nonlinear formulation presented in this chapter has been linearized to be solved by using mixed integer linear programming with the CPLEX 12 GAMS solver. The local energy network under study in this chapter consists of CHP unit, AB, and HS. Inputs of this system are gas and electricity carriers, while the outputs are electricity, gas, and heat. Detailed information on these elements is provided in Table 4.1.

Table 4.1: Data of Local Energy System Elements.

Elements		**P.u.**
CHP	Energy Output (Min-Max)	0-5
	η_h^{CHP}	0.35
	η_e^{CHP}	0.45
	$\underline{\Phi}^{CHP}, \overline{\Phi}^{CHP}$	1, 2
AB	Heat Output (Min-max)	0-10
	η_h^{AB}	0.9
HS	Energy Capacity (Min-Max)	0.5-3
	γ_h^{HS}	1.5
	$\eta_h^{HS,cha}, \eta_h^{HS,dcha}$	0.9, 0.9

The illustration of the results is organized in two sections. Previous section addresses the impact of the dependency existing in the proposed operational model of the LES. Previous section shows and compares the results of stochastic models (representing the uncertainty in customers' choices) and deterministic models. All the studies in this section are first implemented on a base case where the amount of dependent demand is assumed to be zero (leg,t = 0). Then, in each step the level of dependency is increased. However, it is assumed that the total amount of energy that the customers require remains equal in all steps. As a result, the total amount of independent usage of electricity and gas has to be reduced. This reduction is conducted based on the efficiency of electricity and gas production elements in the system.

The information about local energy consumption in the base case and input energy carrier prices is indicated in figures 4.5 and 4.6. In this part, the hot water consumption is considered as the ED that can be supplied by both gas-fired and electrical heaters. The numerical amount of dependency is considered like energy and is expressed in per unit (p.u.).

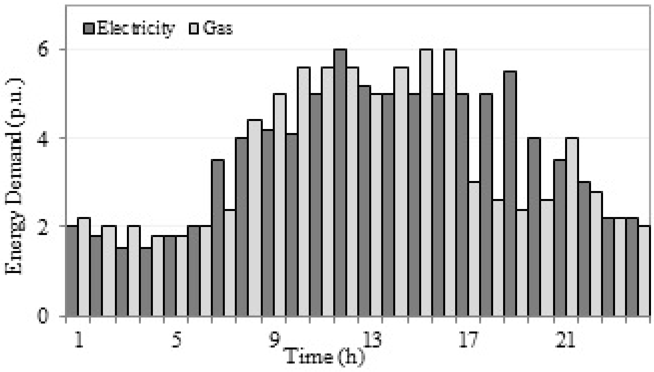

Figure 4.5: Energy carriers demand data in the operation time horizon.

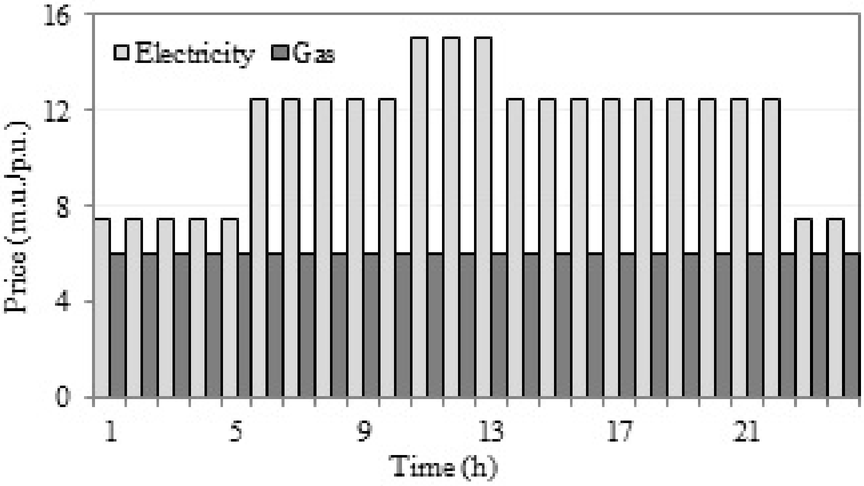

Figure 4.6: Energy carriers price data in the operation time horizon.

The heat demand data is depicted in 4.7. The relation between electricity and gas carrier weighted energy contribution variable in the dependent output of these two carriers is shown in 4.19.

$$\eta_e^{dd} v_{e,\omega,t}^{dd,n} + \eta_g^{dd} v_{g,\omega,t}^{dd,n} = 1 \tag{4.19}$$

where η_e^{dd} and η_g^{dd} are the efficiencies of the electrical and the gas-fired water heaters, respectively. The typical amounts considered for η_e^{dd} and η_g^{dd} are 0.9 and 0.6, respectively, based on [53]. Furthermore, the typical amounts of $v_{e,\omega,t}^{CS}$ and $v_{g,\omega,t}^{CS}$ are

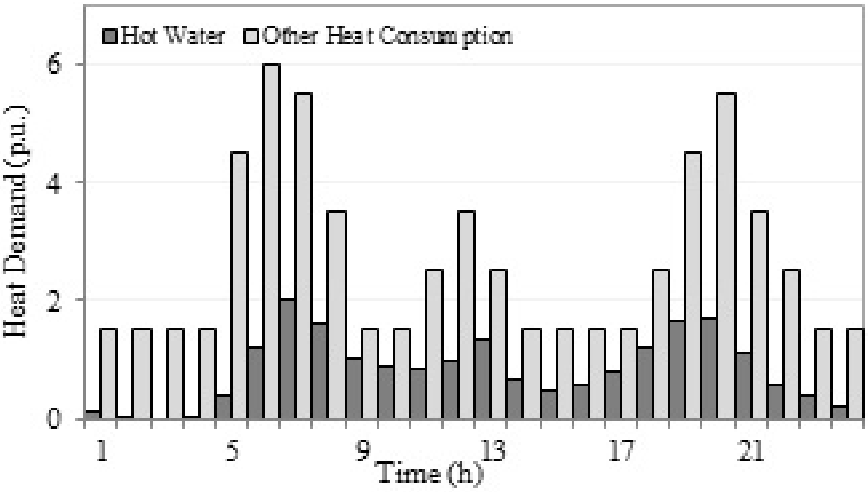

Figure 4.7: Heat demand data in the operation time horizon.

0.26 and 0.74, respectively, based on [103]. In these studies, it is assumed that the system operator enables CBDR by controlling the gas and electricity dependent consumption. This can be achieved by sending one-way communication signals to the multienergy demand, taking advantage of the flexibility brought through this model.

4.5.1 Case I: The Operational Model Study

The first case study regards the impact of dependency and related CBDR programs in the network. The aim is to investigate how the cost of the system and the energy dispatch between the carriers are affected by the dependency existing in the multi-energy demand. Various levels of hot water usage as dependent power in the output are considered ($l_{eg,t}$ varies from 0% up to 100% by intervals of 5%). In addition, five different values for the efficiency η_g^{dd} are assumed, while the efficiency of electricity η_e^{dd} is considered to be fixed. For generating these cases, first, the total amount of the gas and electricity output from the LES to the MED are set up to specific values. Then, as it is assumed that the total amount of output does not change, when the level of dependency increases, part of the previous demand of a carrier does not exist anymore and will be replaced by another carrier. The corresponding demand amount is reduced from the original carrier and is added to the so-called dependency. The energy carriers are adjusted on the basis of the typical output share and efficiency of energy converters. For example, the gas and electricity shares are adjusted based on predetermined η_e^{dd} and η_g^{dd}. Furthermore, the total share of ED is considered for the CBDR program ($l_{\omega,t}^{CB} = L_{eg,t}$).

Figure 4.8 shows the total system cost versus gas-fired heater efficiency for various levels of the demand dependency percentage indicated in 4.17. When the output dependency increases with the same η_e^{dd}, the operational flexibility increases, resulting in lower system operation cost. Conversely, for the same percentage of dependency when η_e^{dd} changes, the costs reach a maximum amount and then gradually decrease. The reason is that, as the output energy amount of LES remains constant, by reducing the gas energy converters' efficiency the system will provide more dependent demand through the electricity carrier. This means that up to a certain point, the operator of the LE still can manage to keep the balance between the total system cost and gas energy carrier's consumption, but after that it is better for the operator to exchange the carrier to another one, electricity in this case.

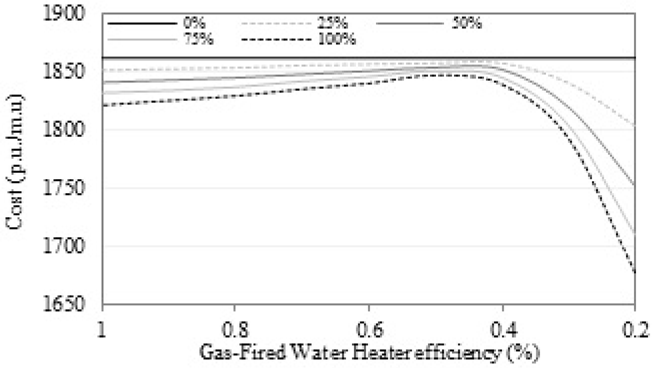

Figure 4.8: LES operation cost based on demand dependency percentage for different water heater efficiencies.

With relatively low efficiency of gas energy converters, the demand requirements can be achieved by taking the benefits of using less electricity with higher efficiency than the gas carrier and in a total view reducing the system operation cost. In other words, when the efficiency of an energy carrier converter on the demand side is too low compared to other carriers in the LES, it is better to change the source of dependent demand to another carrier that produces the required output with higher efficiency.

In general, this case study determines that more proficiency occurs when the LES and MED efficiencies are not close to each other. In this condition, the coordinated decision making between LES and MED will decrease the system's operational cost. The proposed ED model enables the quantification of the operational costs in different conditions.

Figures 4.9 and 4.10 depict the amount of input electricity and gas carriers when η_g^{dd}= 0.6 for various levels of dependency. In these figures, the dependency level is shown for 0% and 100%. The density of the colored region appearing between the 0% and 100% limits indicates that the input quantities change when the dependency level varies. The zoomed-in views included in the figures indicate the corresponding type of variation of the input quantities at a specific hour (7 A.M.).

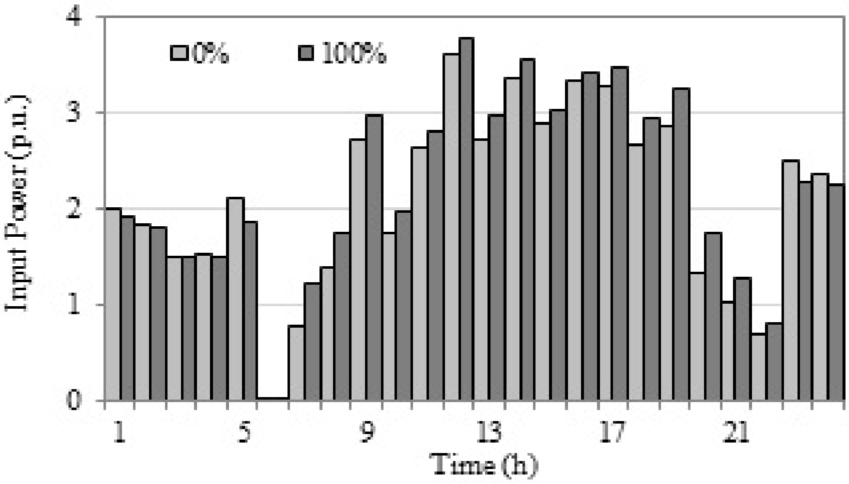

Figure 4.9: Evolution of the electricity input for demand dependency percentage from 0 to 100%, with $\eta_g^{dd} = 0.6$.

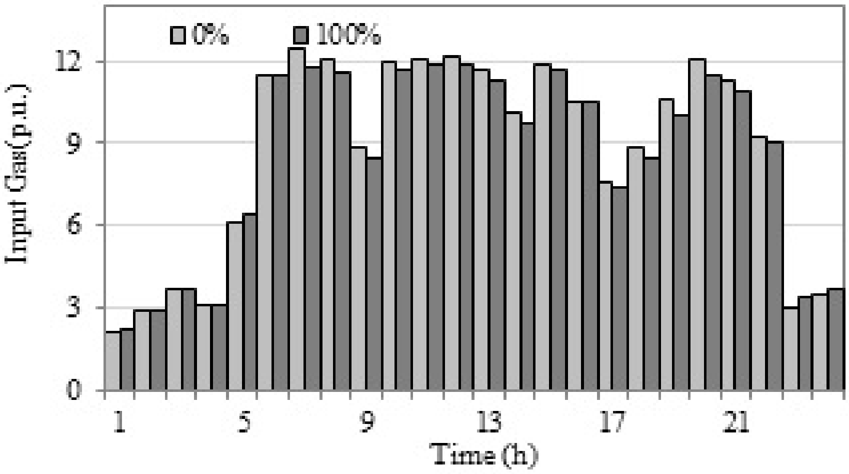

Figure 4.10: Evolution of the gas input for demand dependency percentage from 0 to 100%, with $\eta_g^{dd} = 0.6$.

As it is shown in figures 4.9 and 4.10 at the specific hour 7 A.M., the variation of power and gas input versus increasing variation of demand dependency follows an opposite manner. With increase in dependency percentage the consumption of electricity decreases while the consumption of gas has an increasing trend. The reason is that during hours 6–22 the average electricity price is high; therefore, the system operator prefers to provide the dependent energy amount through gas carrier rather than electricity, which also results in the reduction of the total operation cost. On the other hand, during hours 1–5, 23, and 24, when electricity price is lower, by increasing the level of dependency the tendency for electricity carrier consumption increases, while gas consumption shall decrease.

4.5.2 Case II: Comparison of Stochastic and Deterministic Results

This case study intends to examine the stochastic modeling of the customers' choice and derive the differences with the deterministic model. Data on dependency scenarios is considered based on the input energy carriers' prices, as presented in the Appendix, 4.2. In addition, as shown in 4.11-4.16 and figure 4.4, part of the hot water consumption is dependent on the CBDR program and the other part can be supplied by gas or electricity according to customer's choice.

Table 4.2: Data on Dependency Scenarios.

Time (hours)		**1-5**	**6-10**	**11-13**	**14-22**	**23-24**
CBDR (%)	μ	10	15	20	15	10
	σ	1.66	1.66	1.66	1.66	1.66
Carrier Share (%)	μ	69	74	80	74	69
	σ	5	5	5	5	5

The share of gas and electricity consumption is uncertain because it depends on the consumer's behavior in using electrical and gas-fired water heater and responding to CBDR program. The mentioned uncertainty is considered in the stochastic model. For the sake of a fair comparison, the mean value of the mentioned ratio in the stochastic model is equal to the corresponding amount in the deterministic case. Figures 4.11 and 4.12 compare the share of CBDR and CS from total dependent demand for both gas and electricity carriers of multienergy demand in stochastic and deterministic situations.

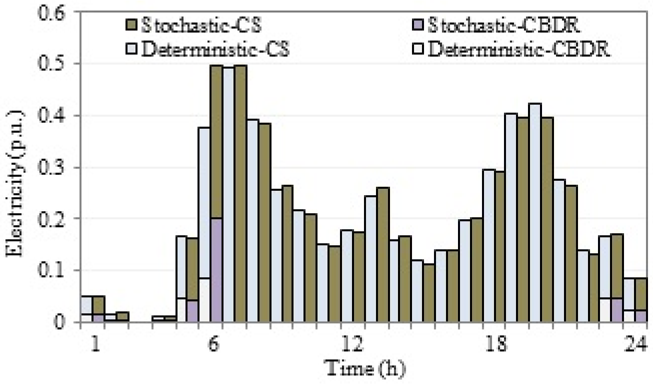

Figure 4.11: Contribution of CBDR and CS to the electricity share of dependent demand for deterministic and stochastic models.

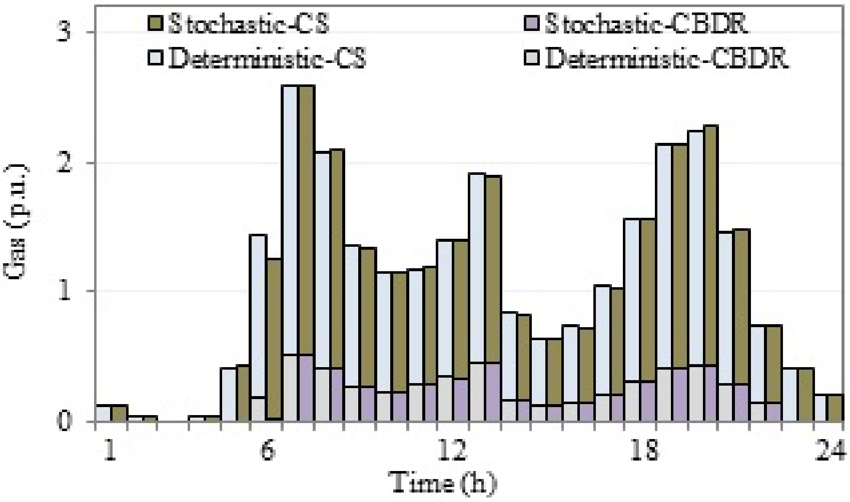

Figure 4.12: Contribution of CBDR and CS in gas share of dependent for deterministic and stochastic models.

From figure 4.11, most of the consumers tend to have their own choice of the electricity carrier for most of the time, with reduced participation in CBDR in early morning and late night. On the other hand, figure 3.29 shows that the consumers have the tendency to take part in the CBDR program for their gas consumption. This tendency occurs mostly between hours 7–22 where no consumer participates in electric CBDR.

From figures 4.11 and 4.12, it can be seen that the results obtained from the deterministic and stochastic models are similar. However, in hour 6 A.M., a significant difference between the results of electricity demand in stochastic and deterministic modeling occurs. The reason is that the assumed system hour 6 A.M. is critical, being the point where the interaction of internal and ED has the highest effect on the operator's decision making. Taking a look at Fig. 6 shows that this hour is the

time when the electricity price shows a rise and will have a significant difference from the gas price. Besides, considering figure 4.7, it shows that at the same hour (6 A.M.) the demand for heat has its highest amount. Therefore, the system operator is going to operate the CHP unit in a way to be able to provide the required heat demand. The CHP unit will be producing more electricity; hence, the system operator will decide to reduce the amount of electricity purchased from the upstream network and supply its customers with the electricity produced by the CHP unit. Fig. 9 proves this and indicates that the amount of electricity purchased at 6 A.M. is zero. The situation shows that, in such hours where high link between internal dependencies and EDs may occur, neglecting the stochastic modeling would affect the results on the balance between power and gas inputs seen by the operator.
Figures 4.13 and 4.14 depict the variations of the input electricity and gas for various scenarios of uncertainty for both CBDR and CS. In these figures, for 900 scenarios, the amount of input energy is illustrated. In these figures, the color code is shown in the figure determining the variation between the lowest (dark blue) and highest (dark red) amount of input energy carrier. The figures are plotted using surfaces with black edges. The black areas in these figures show the density of the scenarios' number that occurred with the same trend. In other words, in those areas, there are more scenarios that have equal amount of input carrier in each hour (or with a very small difference) causing the black edges to overlap and form a black area. It also should be noted that the arrangement of the scenarios are in a way that the scenarios are started from the lowest probability of occurrence, then reach the highest probability and after that the probability decreases again. This means that scenarios with numbers 1–100 and 800–900 have the lowest probability.

In figure 4.13, the black area is concentrated for the scenarios number 200–700. This shows that the scenarios that have higher probability of occurrence tend to follow similar trend, while the other scenarios show high distortion in their results. On the other hand, in figure 4.14, the scenarios do not show a dramatic change in the amount, but overlapping edges show that more probable scenarios exist regarding gas input.
The reason can be found beneath the fact that there are other elements in the LES that help the system operator to damp the effects of harsh uncertain scenarios

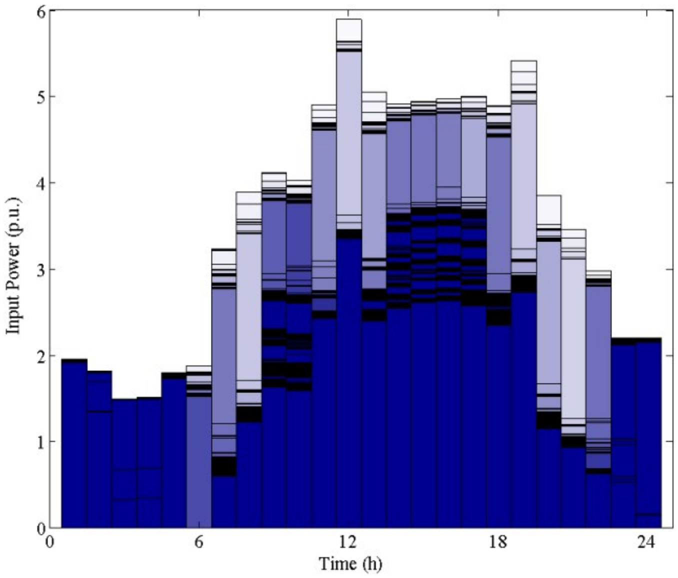

Figure 4.13: Electricity input variation for various stochastic scenarios.

regarding the gas input energy. The AB and CHP unit are two elements that help the supply of gas and heat in the system. As a result, in such systems the uncertainty of end users' stochastic behavior can be managed through the internal dependency in the multienergy system.

The results from the scenarios presented in figures 4.13 and 4.14 are obtained to show the variance of input energy carriers. Figure 4.15 shows that not only the changes in input gas variance are extended to 24 h (while the variance of input power is limited to hours 6–22), but also the amplitude of the variance is higher compared to electricity. The reason is due to various uncertainties that are imposed to the decision making process for the LES's total gas input.

Regarding the gas energy carrier, not only the dependent demand uncertainty should be considered, but also the effects of HS and CHP unit should not be neglected. As the storage has a time-dependent nature, the variance of gas input is extended to various hours. In addition, the CHP unit's consumption of gas and its conflicts with the independent gas consumption and the dependent demand impose other factors to the decision making problem.

For presenting the mechanics of the stochastic model, figure 4.16 shows the variation of total cost versus the variations in CBDR and CS variance. As it is observed, by increase in the CS variance the total cost increases. On the other hand, the increase

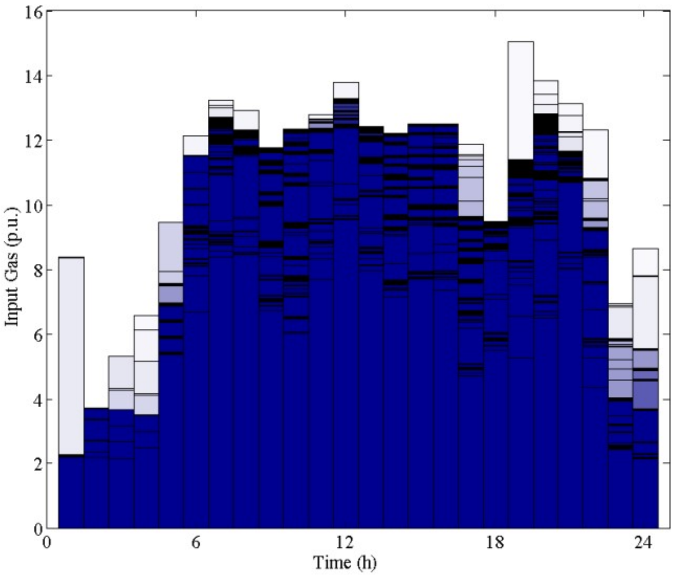

Figure 4.14: Gas input variation for various stochastic scenarios.

in CBDR variance does not impose any significant change in the amount of total cost. The reason is that when the variance of CS is increasing, the uncertainty of customer's choice on different carriers is getting higher. The customer choice referring to CS is not under control by the operator.

Conversely, CBDR is also driven by the operator's action in promoting the DR program, and when the CBDR variance is increasing the operator can maintain its cost through scheduling the consumption of the dependent demand. Moreover, it shows that in higher variances of CS, as the CBDR variance increases the total cost will be reduced. This also indicates that the CBDR program will help the operator to reduce its operation costs.

In order to indicate the performance of the stochastic model, the stored heat is presented as one of the decision variables of the operator in figure 4.17. As it can be seen, the uncertainty of energy carriers' demand in the stochastic model causes the HS to be operated less compared with the deterministic case. The main reason is that a part of stored heat in each hour is wasted as heat loss. Therefore, with higher amount of stored heat more heat loss will be produced in the system, which during the optimization process leads to less utilization of HS from the operator point of view.

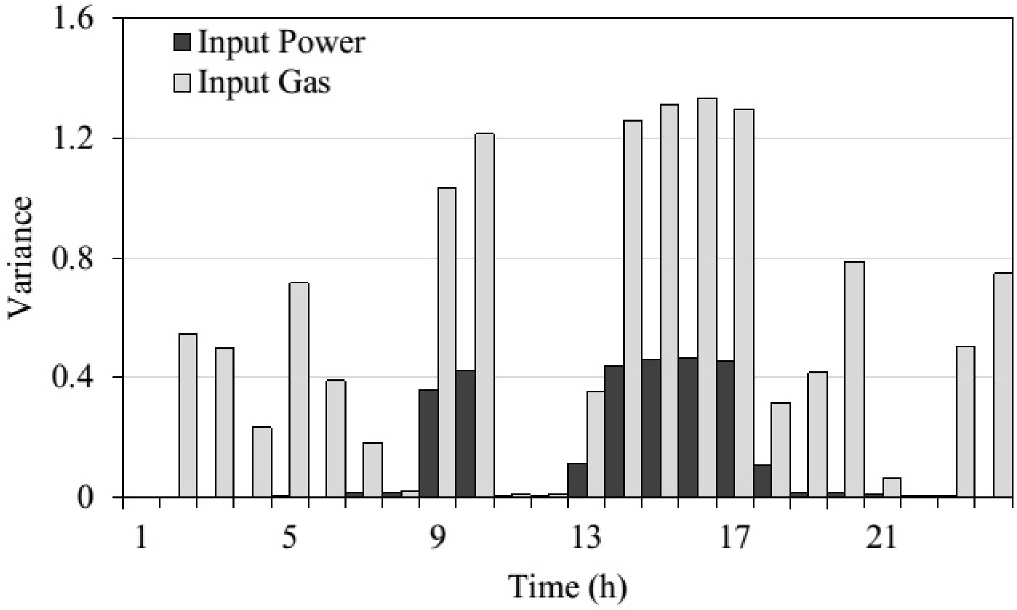

Figure 4.15: Variance of input power and gas.

4.6 Chapter Summary

For a LES, this chapter has introduced the concepts of dependent demand, referring to a specific service that can be supplied through different energy carriers, internal dependencies (referring to changing the energy source in multienergy flows under the control of the system operator) and EDs (representing changes in the energy source driven by the customer choice of the end user, also due to possible participation in DR programs). A new stochastic model based on the energy hub approach has been developed to represent the EDs and their uncertainty referring to multienergy system operation. For assessing the efficiency of the developed model, a local energy system was considered and the uncertain behavior of the consumers was modeled in a stochastic framework. The uncertainties include the response of the customers participating in a CBDR program, and the selection of different carriers by the customers not participating in the CBDR program, both affecting the energy carriers share. The numerical results obtained on a case study show how an increased share of participation in the CBDR program can reduce the operational costs. Furthermore, in networks with inefficient DERs it will be more significant to manage part of the demand as DR programs. In addition, the proposed approach enables quantifying to what extent the stochastic dependencies impact on the operating conditions of

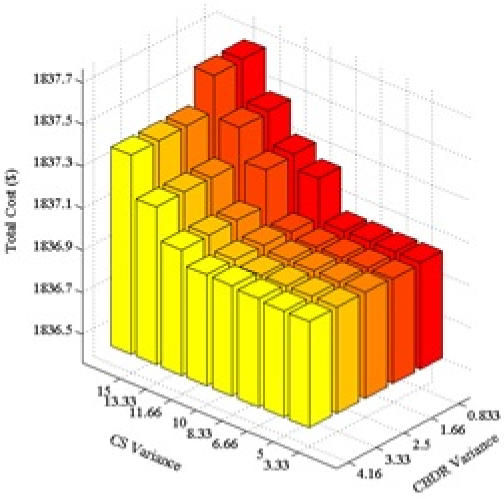

Figure 4.16: Variation of total cost vs. variation in CBDR and CS variance.

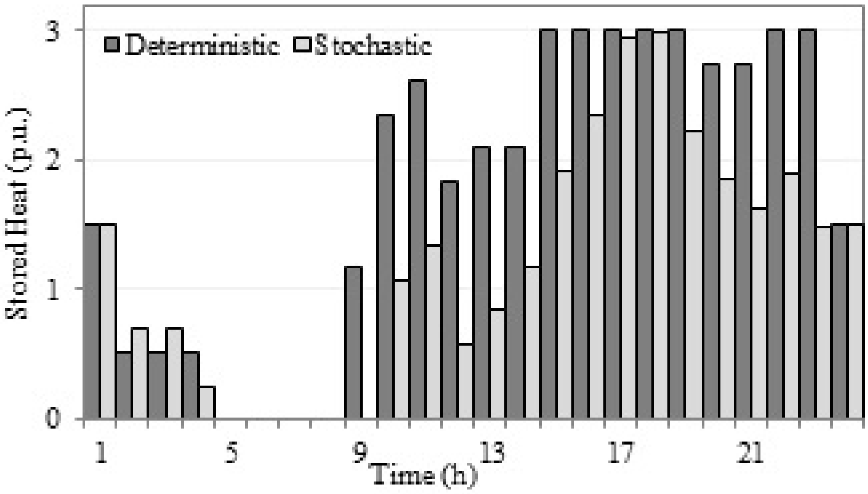

Figure 4.17: Stored heat variation in heat storage for deterministic and stochastic models.

the system and can vary the schedule of the operator because of the more accurate representation of the relevant variables.

Chapter 5

Aggregation of Demand Side Resources Under the Concept of Multi-Energy Players as a Flexible Source

5.1 Problem Description

The main problem addressed in this chapter deals with assessing the level of various regulatory frameworks that facilitate aggregation of MEP in distribution level. MES is considered in four layers namely, wholesale energy markets, MEP, LES, and MED as described in chapter 2. The LES are equipped by DER and interact energy carriers (i.e. electricity, gas, and heat) with other LES and MEP. MEP behaves as an energy aggregator that facilitates energy and financial interaction LES and upstream wholesale energy markets. In addition, three regulatory frameworks namely, centralized management of LES, pay as bid interaction of LES, and uniform interaction approaches are compared in this proposed energy environment. Moreover, in competitive management mode, the behavior of MEP is investigated based on various regulations for energy carriers' price.

Two flexibility indices are introduced from technical and economic points of view to assess various regulatory frameworks that can be applied in local energy systems.

The conflict among decision making of MEP and LES is modeled in competitive management mode based on bi-level approach. In this problem, the upper level is the MEP level that player maximizes its profit while satisfying LES energy exchange. The dictated energy price to the LES is the output of this level. In lower level, LES schedule their energy balance based on the upper level input price signal. The problem is transformed into a mathematical program with equilibrium constraint (MPEC). The model is solved by CPLEX 12 solver through GAMS software. Regarding the above description the main contributions of this section are as follows:

- Proposing an aggregation approach for MEP in distribution level that couples LES based on an equilibrium energy price signal.
- Modeling the proposed framework based on a bi-level approach.
- Introducing two novel indices to assess the flexibility of different regulatory frameworks in distribution level.

5.2 Mathematical Formulation of MES

Figure 5.1 shows the energy and information flow of four layers of MES, namely wholesale energy market, MEP, LES, and MED. MEP trades energy (i.e. electricity and gas) with energy market in predetermined price signal and manages energy exchange (i.e. electricity, gas, and heat) among its LES. On the other hand, LES exchange energy (i.e. electricity, gas, and heat) with MED with time of use (TOU) price and exchange energy in LES level with a competitive price. As a matter of fact, gas and electricity are main energy carriers that trade in all levels but heat is local energy carrier that is only exchanged in LES level.

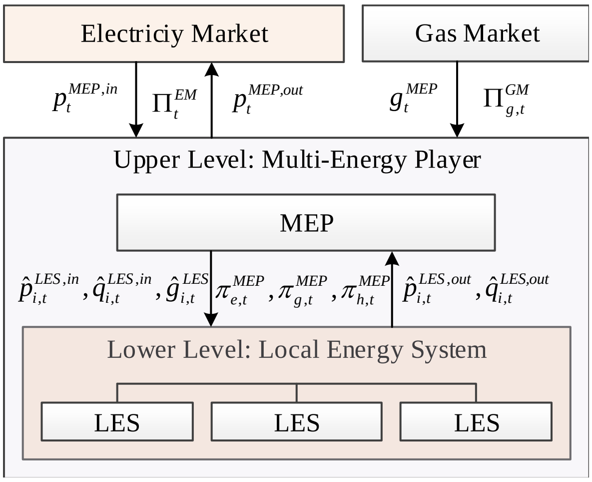

Figure 5.1: Fractal structure of MES and the role of MEP on that.

5.2.1 Multi-Energy Player level

5.2.1.1 Objective Function

MEP aggregates the energy trade of LES and manages the energy exchange among them. The objective of MEP is maximizing its profit that is due to energy exchange with its LES and energy market. The operator has been considered as a price taker player in energy market and trades energy (i.e. gas and electricity) in predetermined price ($\Pi_{e,t}^{MEP}$ and $\Pi_{g,t}^{MEP}$). On the other hand, MEP determines coupling price among LES and LES schedule their energy exchange based on this price. Moreover, LES consist of uncertain energy resources and their energy quantity is indicated based on their internal uncertainty characterization. On the other hand, in MEP level there is no source of uncertainties and LES participate with their expected values of energy exchange in MEP aggregation environment.

$$
\begin{aligned}
maximize \Bigg\{ f(x) = \sum_{t} \Bigg[& - (w_t^{MEP}\Pi_{e,t}^{EM} + g_t^{MEP}\Pi_{g,t}^{GM}) \\
& + \sum_{i} \big(\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP} + \hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP} + \hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP} \big) \Bigg] \Bigg\}
\end{aligned}
\tag{5.1}
$$

5.2.1.2 Constraints

The main constraints of MEP is deal with its energy contract and economical restrictions that appear in energy exchange limits.
Input energy limitation: MEP exchanged energy with energy market is limited by its predetermined energy exchange limits.

$$
\overline{W}^{MEP} \leq w_t^{MEP} \leq \underline{W}^{MEP} \tag{5.2}
$$

$$
0 \leq g_t^{MEP} \leq \underline{G}^{MEP} \tag{5.3}
$$

MEP energy balance: Equations 5.4-5.6 demonstrate the energy balance in MEP for electricity, gas, and heat, respectively. The heat is local energy carrier and its energy balance is based on the energy exchange among LES while the electricity and gas energy balance should be determined based on the both energy exchange with energy market and LES.

$$w_t^{MEP} - \sum_i \hat{w}_{i,t}^{LES} = 0 \tag{5.4}$$

$$g_t^{MEP} - \sum_i \hat{g}_{i,t}^{LES} = 0 \tag{5.5}$$

$$\sum_i \hat{q}_{i,t}^{LES} = 0 \tag{5.6}$$

5.2.2 Local Energy System Level

Equations 5.7 and 5.8 demonstrate the general form of optimization problem for LES. The $\mathbf{f_i X_i}$ is the vector of objective functions for LES and is optimized based on their internal energy schedule and energy exchange in MEP level.

$$\begin{gathered} minimizing \ \{\mathbf{f_i X_i}\} \\ Sub.\,to: \mathbf{H_i X_i} - \mathbf{b_i} \geqslant \mathbf{0} \\ \Rightarrow \begin{cases} \mathbf{E_i(X_i)}: \mathbf{H_i^E X_i} = \mathbf{0} \\ \mathbf{N_i(X_i)}: \mathbf{H_i^N X_i} - \mathbf{b_i^N} \geqslant \mathbf{0} \end{cases} \\ \mathbf{X_i} \geqslant \mathbf{0} \end{gathered} \tag{5.7}$$

$$\mathbf{H_i} = \begin{bmatrix} \mathbf{H_i^E} \\ \mathbf{H_i^N} \end{bmatrix}, \mathbf{b_i} = \begin{bmatrix} \mathbf{0} \\ \mathbf{b_i^N} \end{bmatrix} \tag{5.8}$$

where $\mathbf{E_i(X_i)}$ and $\mathbf{N_i(X_i)}$ are vectors of equality and inequality constraints, respectively.

5.2.2.1 Objective Function

The objective of LES is maximizing its profit from selling energy to MED and trading energy with MEP while meeting the operational constraints of its internal energy elements. Equations 5.10-5.12 describe the expected values of LES energy exchange with the MEP.

$$\begin{aligned} &minimizing \Bigg\{ \mathbf{f_i X_i} = \sum_t \Bigg[\Big(\hat{w}^{LES}_{i,t}\pi^{MEP}_{e,i,t} + \hat{g}^{LES}_{i,t}\pi^{MEP}_{g,i,t} + \hat{q}^{LES}_{i,t}\pi^{MEP}_{h,i,t} \Big) \\ &- \Big((W^{MED}_{i,t} - W^{IL}_{i,t})\Pi^{MED}_{e,i,t} + G^{MED}_{i,t}\Pi^{MED}_{g,i,t} + Q^{MED}_{i,t}\Pi^{MED}_{h,i,t} - W^{IL}_{i,t}\Pi^{IL,inc}_{i,t} \Big) \Bigg] \Bigg\} \end{aligned} \tag{5.9}$$

$$\hat{w}^{LES}_{i,t} = \sum_{\omega} \rho_{\omega} \big(w^{LES,in}_{i,\omega,t} - w^{LES,out}_{i,\omega,t} \big) \tag{5.10}$$

$$\hat{q}^{LES}_{i,t} = \sum_{\omega} \rho_{\omega} \big(q^{LES,in}_{i,\omega,t} - q^{LES,out}_{i,\omega,t} \big) \tag{5.11}$$

$$\hat{g}^{LES}_{i,t} = \sum_{\omega} \rho_{\omega} g^{LES}_{i,\omega,t} \tag{5.12}$$

5.2.2.2 Constraints

Energy Balance: Equations 5.2.2.2-5.2.2.2 demonstrate energy balance for gas, heat, and electricity, respectively in LES which are based on internal energy exchange of energy components i.e. combined heat and power (CHP), auxiliary boiler (AB), heat storage (HS), and interruptible load (IL). Moreover, the dual variable of each constraint is represented in the right hand side of the respected equation.

$$\begin{aligned} E^{LES,1}_{i,\omega,t} &= W^{MED}_{i,t} - w^{IL}_{i,\omega,t} - w^{CHP}_{i,\omega,t} - w^{LES,in}_{i,\omega,t}\eta^{Trans}_{e,i} \\ &+ w^{LES,out}_{i,\omega,t}/\eta^{Trans}_{e,i} - w^{Wind}_{i,\omega,t} - w^{PV}_{i,\omega,t} = 0 \qquad : \lambda^{MED}_{e,i,t} \end{aligned} \tag{5.13}$$

$$E^{LES,2}_{i,\omega,t} = G^{MED}_{i,t} - g^{LES}_{i,\omega,t} + g^{CHP}_{i,\omega,t} + g^{AB}_{i,\omega,t} \qquad : \lambda^{MED}_{g,i,t} \tag{5.14}$$

$$\begin{aligned} E^{LES,3}_{i,\omega,t} &= Q^{MED}_{i,t} - q^{LES,in}_{i,\omega,t}\eta^{LES}_{h,i} + q^{LES,out}_{i,\omega,t}/\eta^{LES}_{h,i} \\ &+ q^{HS,in}_{i,\omega,t} - q^{HS,out}_{i,\omega,t} - q^{CHP}_{i,\omega,t} - q^{AB}_{i,\omega,t} = 0 \qquad : \lambda^{MED}_{h,i,t} \end{aligned} \tag{5.15}$$

Input energy limitation: The input and output energy of LES are restricted by interconnectors' capacity as following:

$$
\begin{aligned}
N^{LES,1}_{i,\omega,t}, N^{LES,2}_{i,\omega,t} &: 0 \leq w^{LES,in}_{i,\omega,t} \leq \overline{W}^{LES}_{i} && : \underline{\mu}^{LES,in}_{e,i,\omega,t}, \overline{\mu}^{LES,in}_{e,i,\omega,t} \quad (5.16)\\
N^{LES,3}_{i,\omega,t}, N^{LES,4}_{i,\omega,t} &: 0 \leq w^{LES,out}_{i,\omega,t} \leq \overline{W}^{LES}_{i} && : \underline{\mu}^{LES,out}_{e,i,\omega,t}, \overline{\mu}^{LES,out}_{e,i,\omega,t} \quad (5.17)\\
N^{LES,5}_{i,\omega,t}, N^{LES,6}_{i,\omega,t} &: 0 \leq q^{LES,in}_{i,\omega,t} \leq \overline{Q}^{LES}_{i} && : \underline{\mu}^{LES,in}_{h,i,\omega,t}, \overline{\mu}^{LES,in}_{h,i,\omega,t} \quad (5.18)\\
N^{LES,7}_{i,\omega,t}, N^{LES,8}_{i,\omega,t} &: 0 \leq q^{LES,out}_{i,\omega,t} \leq \overline{Q}^{LES}_{i} && : \underline{\mu}^{LES,out}_{h,i,\omega,t}, \overline{\mu}^{LES,out}_{h,i,\omega,t} \quad (5.19)\\
N^{LES,9}_{i,\omega,t}, N^{LES,10}_{i,\omega,t} &: 0 \leq g^{LES}_{i,\omega,t} \leq \overline{G}^{LES}_{i} && : \underline{\mu}^{LES}_{g,i,\omega,t}, \overline{\mu}^{LES}_{g,i,\omega,t} \quad (5.20)
\end{aligned}
$$

CHP operational constraints: The CHP unit consumes gas and generates electricity and heat (5.21 and 5.22). Moreover, the amount of the heat and electricity production are restricted based on characteristics (5.23-5.25) of the unit while its heat to electricity ratio (Φ^{CHP}_{i}) is a constant value.

$$
\begin{aligned}
E^{LES,4}_{i,\omega,t} &= w^{CHP}_{i,\omega,t} - \eta^{CHP}_{e,i} g^{CHP}_{i,\omega,t} = 0 && : \lambda^{CHP}_{e,i,\omega,t} \quad (5.21)\\
E^{LES,5}_{i,\omega,t} &= q^{CHP}_{i,\omega,t} - \eta^{CHP}_{h,i} g^{CHP}_{i,\omega,t} = 0 && : \lambda^{CHP}_{h,i,\omega,t} \quad (5.22)\\
N^{LES,11}_{i,\omega,t}, N^{LES,12}_{i,\omega,t} &: 0 \leq w^{CHP}_{i,\omega,t} \leq \overline{W}^{CHP}_{i} && : \underline{\mu}^{CHP}_{e,i,\omega,t}, \overline{\mu}^{CHP}_{e,i,\omega,t} \quad (5.23)\\
N^{LES,13}_{i,\omega,t}, N^{LES,14}_{i,\omega,t} &: 0 \leq q^{CHP}_{i,\omega,t} \leq \overline{Q}^{CHP}_{i} && : \underline{\mu}^{CHP}_{h,i,\omega,t}, \overline{\mu}^{CHP}_{h,i,\omega,t} \quad (5.24)\\
E^{LES,6}_{i,\omega,t} &= w^{CHP}_{i,\omega,t} \Phi^{CHP}_{i} - q^{CHP}_{i,\omega,t} = 0 && : \lambda^{Ratio}_{i,\omega,t} \quad (5.25)
\end{aligned}
$$

AB operational constraints: The output heat of AB is related to its efficiency and should be lower than its maximum capacity.

$$
\begin{aligned}
E^{LES,7}_{i,\omega,t} &= q^{AB}_{i,\omega,t} - \eta^{AB}_{e,i} g^{AB}_{i,\omega,t} = 0 && : \lambda^{AB}_{h,i,\omega,t} \quad (5.26)\\
N^{LES,15}_{i,\omega,t}, N^{LES,16}_{i,\omega,t} &: 0 \leq q^{AB}_{i,\omega,t} \leq \overline{Q}^{AB}_{i} && : \underline{\mu}^{AB}_{h,i,\omega,t}, \overline{\mu}^{AB}_{h,i,\omega,t} \quad (5.27)
\end{aligned}
$$

HS operational constraints: The stored heat in each hour is related to energy exchange of HS with LES and should be lower than HS limitations. Moreover, for determining HS energy consistency in the study period the amount of the stored energy in starting and ending hours of period are considered as half of maximum capacity.

$$E_{i,\omega,t}^{LES,8} = q_{i,\omega,t}^{HS} - q_{i,\omega,t-1}^{HS}\Big|_{t>1} - 0.5Q_{i,\omega,t}^{HS}\Big|_{t=1} + q_{i,\omega,t}^{HS,in}\eta_{h,i}^{HS}$$

$$-q_{i,\omega,t}^{HS,out}/\eta_{h,i}^{HS} = 0 \qquad : \lambda_{h,i,\omega,t}^{HS} \tag{5.28}$$

$$N_{i,\omega,t}^{LES,17}, N_{i,\omega,t}^{LES,18} : 0 \leq q_{i,\omega,t}^{HS,in} \leq \gamma_i^{HS} \qquad : \underline{\mu}_{h,i,\omega,t}^{HS,in}, \overline{\mu}_{h,i,\omega,t}^{HS,in} \tag{5.29}$$

$$N_{i,\omega,t}^{LES,19}, N_{i,\omega,t}^{LES,20} : 0 \leq q_{i,\omega,t}^{HS,out} \leq \gamma_i^{HS} \qquad : \underline{\mu}_{h,i,\omega,t}^{HS,out}, \overline{\mu}_{h,i,\omega,t}^{HS,out} \tag{5.30}$$

$$N_{i,\omega,t}^{LES,21}, N_{i,\omega,t}^{LES,22} : 0 \leq q_{i,\omega,t}^{HS} \leq \overline{Q}_i^{HS} \qquad : \underline{\mu}_{h,i,\omega,t}^{HS}, \overline{\mu}_{h,i,\omega,t}^{HS} \tag{5.31}$$

$$T_{i,\omega,t}^{LES,1}, T_{i,\omega,t}^{LES,2} : q_{i,\omega,t}^{HS}\Big|_{t=1} = q_{i,\omega,t}^{HS}\Big|_{t=T} = Q_{i,\omega,t}^{HS}/2 \qquad : \xi_{h,i,\omega,t}^{HS}\Big|_{t=1}, \xi_{h,i,\omega,t}^{HS}\Big|_{t=T}$$

PV arrays operational constraint: Some scenario are implemented to model the uncertain nature of PV array generation. The generation in each hour should be based on the scenario amounts.

$$N_{i,\omega,t}^{LES,23}, N_{i,\omega,t}^{LES,24} : 0 \leq w_{i,\omega,t}^{PV} \leq \overline{W}_i^{PV,Forecast} \qquad : \underline{\mu}_{e,i,\omega,t}^{PV}, \overline{\mu}_{e,i,\omega,t}^{PV} \tag{5.32}$$

Wind generation operational constraint: Similar to PV array, for wind generation, the output energy is based on wind scenario.

$$N_{i,\omega,t}^{LES,25}, N_{i,\omega,t}^{LES,26} : 0 \leq w_{i,\omega,t}^{Wind} \leq \overline{W}_i^{Wind,Forecast} \qquad : \underline{\mu}_{e,i,\omega,t}^{Wind}, \overline{\mu}_{e,i,\omega,t}^{Wind} \tag{5.33}$$

Interruptible load: LES operator gives an incentive to the MED to reduce its consumption while the input energy price is high and the energy production is not profitable for LES. In this chapter the IL is only considered for electricity and $\alpha_{i,t}^{IL}$ is the percentage of electrical demand that can be interrupted.

$$N_{i,\omega,t}^{LES,27}, N_{i,\omega,t}^{LES,28} : 0 \leq w_{i,\omega,t}^{IL} \leq \alpha_{i,t}^{IL} W_{i,t}^{MED} \qquad : \underline{\mu}_{e,i,\omega,t}^{IL}, \overline{\mu}_{e,i,\omega,t}^{IL} \tag{5.34}$$

5.3 Mathematical Formulation of MEP and LES Desicion Making Conflict

Based on the proposed formulation, MEP and LES are assumed in two levels. The model can be considered as a Stakelberg game that in the upper level there is a

MEP as a leader and in the lower level there are LES as followers. MEP determines the energy price and LES schedule their internal energy resources and propose their energy exchange based on the coupling price. This bi-level MINLP problem can be transformed to an MILP single level problem based on the following procedure ([104] and [105]):

- Transforming the lower level problem to a convex and linear problem;
- Considering the upper level signal price as an input parameter for the lower level;
- Indeed, the lower level problems can be replaced by their Karush-Kuhn-Tucker (KKT) optimality conditions.
- Implementing strong duality theorem to linearize the nonlinear terms of the upper level objective function (i.e. $\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}$).

5.3.1 MPEC Formulation of LES Level

5.3.1.1 Comprehensive Model

The LES equations are linear and in convex format (5.2.2.2-5.35). For replacing the lower level problem with its KKT optimality conditions, 5.35 determines the Lagrangian expression of lower level problem. μ_i, λ_i, and ξ_i are dual variables of LES inequality constraints, equality constraints, and equality constraints in specific time intervals, respectively. Equations 5.37-5.40 represent KKT conditions of the lower level problem that can be replaced by lower level optimization problem. Equation 5.36 is stationarity condition, eq.s 5.37 and 5.38 are primal feasibility conditions, and 5.39 is complementarity condition of KKT optimality conditions.

$$\mathcal{L}_i = \mathbf{f_i}(\mathbf{X_i}) - \mu_\mathbf{i}\mathbf{N_i}(\mathbf{X_i}) + \lambda_\mathbf{i}\mathbf{E_i}(\mathbf{X_i}) + \xi_\mathbf{i}\mathbf{T_i}(\mathbf{X_i}) \tag{5.35}$$

$$\partial\mathcal{L}_i/\partial\mathbf{X_i} = \mathbf{0} \tag{5.36}$$

$$\partial\mathcal{L}_i/\partial\lambda_\mathbf{i} = \mathbf{E_i}(\mathbf{X_i}) = \mathbf{0} \tag{5.37}$$

$$\partial\mathcal{L}_i/\partial\xi_\mathbf{i} = \mathbf{T_i}(\mathbf{X_i}) = \mathbf{0} \tag{5.38}$$

$$0 \leqslant \mu_\mathbf{i} \perp \mathbf{N_i}(\mathbf{X_i}) \geqslant \mathbf{0} \tag{5.39}$$

For linearizing complementarity conditions a set of binary variables ($\mathbf{u_i}$) are implemented to transform the equation 5.39 to equations 5.40 and 5.41 [105].

$$0 \leqslant \mathbf{N_i}(\mathbf{X_i}) \leqslant \mathbf{u}_i \ M^p \tag{5.40}$$

$$0 \leqslant \mu_\mathbf{i} \leqslant \mathbf{u}_i \ M^d \tag{5.41}$$

Equation 5.42 shows the dual format of lower level problem (eq. 5.7). Λ_i is the vector of dual variables of LES constraints which have been determined in the right hand of equations 5.2.2.2-5.35.

$$\begin{gathered} maximizing \ \mathbf{b_i^T \Lambda_i} \\ Sub.\ to: \mathbf{H_i^T \Lambda_i} \leqslant \mathbf{f_i^T} \quad (5.42) \\ \mathbf{\Lambda_i} \geqslant \mathbf{0} \end{gathered}$$

Equation 5.43 illustrates the strong duality condition for the lower level problem. This condition states that, if the lower level problem is convex and linear, the gap of dual and primal objective functions can be considered as zero and the objective functions of primal and dual problems are equaled to each other [104]. The nonlinear terms of MEP objective function ($\hat{w}_{i,t}^{LES}\pi_{e,i,t}^{MEP}$, $\hat{g}_{i,t}^{LES}\pi_{g,i,t}^{MEP}$, and $\hat{q}_{i,t}^{LES}\pi_{h,i,t}^{MEP}$) are as the same as the nonlinear terms of the objective function of LES. Therefore, they can be replaced based on 5.43 by their linear formats which are derived from strong duality condition.

$$\mathbf{f_i X_i} = \mathbf{b_i^T \Lambda_i} \tag{5.43}$$

5.3.1.2 Detailed Model

Based on the comprehensive model description, the lagrangian expression, complementary, and stationary conditions of lower level problem are represented as follow, respectively.

Lagrangian Expression:

$$\mathcal{L}_i^{LES} = \left((w_{i,\omega,t}^{LES,in} - w_{i,\omega,t}^{LES,out})\pi_{e,i,t}^{MEP} + g_{i,\omega,t}^{LES}\pi_{g,i,t}^{MEP} + (q_{i,\omega,t}^{LES,in} - q_{i,\omega,t}^{LES,out})\pi_{h,i,t}^{MEP} \right) \tag{5.44}$$

$$\begin{gathered}
-\left((W_{i,t}^{MED} - W_{i,t}^{IL})\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\Pi_{h,i,t}^{MED} - W_{i,t}^{IL}\Pi_{i,t}^{IL,inc} \right) \\
+\lambda_{e,i,t}^{MED}(W_{i,t}^{MED} - w_{i,\omega,t}^{IL} - w_{i,\omega,t}^{CHP} - w_{i,\omega,t}^{LES,in}\eta_{e,i}^{Trans} + w_{i,\omega,t}^{LES,out}/\eta_{e,i}^{Trans} - w_{i,\omega,t}^{Wind} - w_{i,\omega,t}^{PV}) \\
+\lambda_{g,i,t}^{MED}(G_{i,t}^{MED} - g_{i,\omega,t}^{LES} + g_{i,\omega,t}^{CHP} + g_{i,\omega,t}^{AB}) \\
+\lambda_{h,i,t}^{MED}(Q_{i,t}^{MED} - q_{i,\omega,t}^{LES,in}\eta_{h,i}^{LES} + q_{i,\omega,t}^{LES,out}/\eta_{h,i}^{LES} + q_{i,\omega,t}^{HS,in} - q_{i,\omega,t}^{HS,out} - q_{i,\omega,t}^{CHP} - q_{i,\omega,t}^{AB}) \\
+\lambda_{e,i,\omega,t}^{CHP}(w_{i,\omega,t}^{CHP} - \eta_{e,i}^{CHP} g_{i,\omega,t}^{CHP}) \\
+\lambda_{h,i,\omega,t}^{CHP}(q_{i,\omega,t}^{CHP} - \eta_{h,i}^{CHP} g_{i,\omega,t}^{CHP}) \\
+\lambda_{i,\omega,t}^{Ratio}(w_{i,\omega,t}^{CHP}\Phi_i^{CHP} - q_{i,\omega,t}^{CHP}) \\
+\lambda_{h,i,\omega,t}^{AB}(q_{i,\omega,t}^{AB} - \eta_{h,i}^{AB} g_{i,\omega,t}^{AB}) \\
+\lambda_{h,i,\omega,t}^{HS}(q_{i,\omega,t}^{HS} - q_{i,\omega,t-1}^{HS}\Big|_{t>1} - 0.5Q_{i,\omega,t}^{HS}\Big|_{t=1} + q_{i,\omega,t}^{HS,in}\eta_{h,i}^{HS} - q_{i,\omega,t}^{HS,out}/\eta_{h,i}^{HS}) \\
+\xi_{h,i,\omega,t}^{HS}\Big|_{t=1}(q_{i,\omega,t}^{HS}\Big|_{t=1} - Q_{i,\omega,t}^{HS}/2) \\
+\xi_{h,i,\omega,t}^{HS}\Big|_{t=T}(q_{i,\omega,t}^{HS}\Big|_{t=T} - Q_{i,\omega,t}^{HS}/2) \\
-\underline{\mu}_{e,i,\omega,t}^{LES,in}(w_{i,\omega,t}^{LES,in}) - \overline{\mu}_{e,i,\omega,t}^{LES,in}(\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,in}) \\
-\underline{\mu}_{e,i,\omega,t}^{LES,out}(w_{i,\omega,t}^{LES,out}) - \overline{\mu}_{e,i,\omega,t}^{LES,out}(\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,out}) \\
-\underline{\mu}_{h,i,\omega,t}^{LES,in}(q_{i,\omega,t}^{LES,in}) - \overline{\mu}_{h,i,\omega,t}^{LES,in}(\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,in}) \\
-\underline{\mu}_{h,i,\omega,t}^{LES,out}(q_{i,\omega,t}^{LES,out}) - \overline{\mu}_{h,i,\omega,t}^{LES,out}(\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,out}) \\
-\underline{\mu}_{g,i,\omega,t}^{LES}(g_{i,\omega,t}^{LES}) - \overline{\mu}_{g,i,\omega,t}^{LES}(\overline{G}_i^{LES} - g_{i,\omega,t}^{LES}) \\
-\underline{\mu}_{e,i,\omega,t}^{CHP}(w_{i,\omega,t}^{CHP}) - \overline{\mu}_{e,i,\omega,t}^{CHP}(\overline{W}_i^{CHP} - w_{i,\omega,t}^{CHP}) \\
-\underline{\mu}_{h,i,\omega,t}^{CHP}(q_{i,\omega,t}^{CHP}) - \overline{\mu}_{h,i,\omega,t}^{CHP}(\overline{Q}_i^{CHP} - q_{i,\omega,t}^{CHP}) \\
-\underline{\mu}_{h,i,\omega,t}^{AB}(q_{i,\omega,t}^{AB}) - \overline{\mu}_{h,i,\omega,t}^{AB}(\overline{Q}_i^{AB} - q_{i,\omega,t}^{AB}) \\
-\underline{\mu}_{h,i,\omega,t}^{HS,in}(q_{i,\omega,t}^{HS,in}) - \overline{\mu}_{h,i,\omega,t}^{HS,in}(\gamma_i^{HS} - q_{i,\omega,t}^{HS,in}) \\
-\underline{\mu}_{h,i,\omega,t}^{HS,out}(q_{i,\omega,t}^{HS,out}) - \overline{\mu}_{h,i,\omega,t}^{HS,out}(\gamma_i^{HS} - q_{i,\omega,t}^{HS,out})
\end{gathered}$$

$$-\underline{\mu}^{HS}_{h,i,\omega,t}(q^{HS}_{i,\omega,t}) - \overline{\mu}^{HS}_{h,i,\omega,t}(\overline{Q}^{HS}_{i} - q^{HS}_{i,\omega,t})$$

$$-\underline{\mu}^{PV}_{e,i,\omega,t}(w^{PV}_{i,\omega,t}) - \overline{\mu}^{PV}_{e,i,\omega,t}(\overline{W}^{PV,Forecast}_{i} - w^{PV}_{i,\omega,t})$$

$$-\underline{\mu}^{Wind}_{e,i,\omega,t}(w^{Wind}_{i,\omega,t}) - \overline{\mu}^{Wind}_{e,i,\omega,t}(\overline{W}^{Wind,Forecast}_{i} - w^{Wind}_{i,\omega,t})$$

$$-\underline{\mu}^{IL}_{e,i,\omega,t}(w^{IL}_{i,\omega,t}) - \overline{\mu}^{IL}_{e,i,\omega,t}(\alpha^{IL}_{i,t}W^{MED}_{i,t} - w^{IL}_{i,\omega,t})$$

Stationary Condition:

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{LES,in}_{i,\omega,t} = \pi^{MEP}_{e,i,t} - \lambda^{MED}_{e,i,t}\eta^{Trans}_{e,i} - \underline{\mu}^{LES,in}_{e,i,\omega,t} + \overline{\mu}^{LES,in}_{e,i,\omega,t} = 0 \tag{5.45}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{LES,out}_{i,\omega,t} = -\pi^{MEP}_{e,i,t} + \lambda^{MED}_{e,i,t}/\eta^{Trans}_{e,i} - \underline{\mu}^{LES,out}_{e,i,\omega,t} + \overline{\mu}^{LES,out}_{e,i,\omega,t} = 0 \tag{5.46}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial g^{LES}_{i,\omega,t} = \pi^{MEP}_{g,i,t} - \lambda^{MED}_{e,i,t} - \underline{\mu}^{LES}_{g,i,\omega,t} + \overline{\mu}^{LES}_{g,i,\omega,t} = 0 \tag{5.47}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{LES,in}_{i,\omega,t} = \pi^{MEP}_{h,i,t} - \lambda^{MED}_{h,i,t}\eta^{LES}_{h,i} - \underline{\mu}^{LES,in}_{h,i,\omega,t} + \overline{\mu}^{LES,in}_{h,i,\omega,t} = 0 \tag{5.48}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{LES,out}_{i,\omega,t} = \pi^{MEP}_{h,i,t} + \lambda^{MED}_{h,i,t}/\eta^{LES}_{h,i} - \underline{\mu}^{LES,out}_{h,i,\omega,t} + \overline{\mu}^{LES,out}_{h,i,\omega,t} = 0 \tag{5.49}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{CHP}_{i,\omega,t} = -\lambda^{MED}_{e,i,t} + \lambda^{CHP}_{e,i,\omega,t} + \lambda^{Ratio}_{i,\omega,t}\Phi^{CHP}_{i} - \underline{\mu}^{CHP}_{e,i,\omega,t} + \overline{\mu}^{CHP}_{e,i,\omega,t} = 0 \tag{5.50}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{CHP}_{i,\omega,t} = -\lambda^{MED}_{h,i,t} + \lambda^{CHP}_{h,i,\omega,t} - \lambda^{Ratio}_{i,\omega,t} - \underline{\mu}^{CHP}_{h,i,\omega,t} + \overline{\mu}^{CHP}_{h,i,\omega,t} = 0 \tag{5.51}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial g^{CHP}_{i,\omega,t} = \lambda^{MED}_{g,i,t} - \lambda^{CHP}_{e,i,\omega,t}\eta^{CHP}_{e,i} - \lambda^{CHP}_{h,i,\omega,t}\eta^{CHP}_{h,i} = 0 \tag{5.52}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{AB}_{i,\omega,t} = -\lambda^{MED}_{h,i,t} + \lambda^{AB}_{h,i,\omega,t} - \underline{\mu}^{AB}_{h,i,\omega,t} + \overline{\mu}^{AB}_{h,i,\omega,t} = 0 \tag{5.53}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial g^{AB}_{i,\omega,t} = +\lambda^{MED}_{g,i,t} - \lambda^{AB}_{h,i,\omega,t}\eta^{AB}_{h,i} = 0 \tag{5.54}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{HS,in}_{i,\omega,t} = +\lambda^{MED}_{h,i,t} + \lambda^{HS}_{h,i,\omega,t}\eta^{HS}_{h,i} - \underline{\mu}^{HS,in}_{h,i,\omega,t} + \overline{\mu}^{HS,in}_{h,i,\omega,t} = 0 \tag{5.55}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{HS,out}_{i,\omega,t} = -\lambda^{MED}_{h,i,t} - \lambda^{HS}_{h,i,\omega,t}/\eta^{HS}_{h,i} - \underline{\mu}^{HS,out}_{h,i,\omega,t} + \overline{\mu}^{HS,out}_{h,i,\omega,t} = 0 \tag{5.56}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial q^{HS}_{i,\omega,t} = +\lambda^{HS}_{h,i,\omega,t} - \lambda^{HS}_{h,i,\omega,t+1} - \underline{\mu}^{HS}_{h,i,\omega,t} + \overline{\mu}^{HS}_{h,i,\omega,t} = 0 \tag{5.57}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{Wind}_{i,\omega,t} = -\lambda^{MED}_{e,i,t} - \underline{\mu}^{Wind}_{e,i,\omega,t} + \overline{\mu}^{Wind}_{e,i,\omega,t} = 0 \tag{5.58}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{PV}_{i,\omega,t} = -\lambda^{MED}_{e,i,t} - \underline{\mu}^{PV}_{e,i,\omega,t} + \overline{\mu}^{PV}_{e,i,\omega,t} = 0 \tag{5.59}$$

$$\partial\mathcal{L}^{LES}_{i}/\partial w^{IL}_{i,\omega,t} = -\lambda^{MED}_{e,i,t} - \underline{\mu}^{IL}_{e,i,\omega,t} + \overline{\mu}^{IL}_{e,i,\omega,t} = 0 \tag{5.60}$$

Complementary Condition:

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{LES,in} \perp (w_{i,\omega,t}^{LES,in}) \geqslant 0 \tag{5.61}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{LES,in} \perp (\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,in}) \geqslant 0 \tag{5.62}$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{LES,out} \perp (w_{i,\omega,t}^{LES,out}) \geqslant 0 \tag{5.63}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{LES,out} \perp (\overline{W}_i^{LES} - w_{i,\omega,t}^{LES,out}) \geqslant 0 \tag{5.64}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{LES,in} \perp (q_{i,\omega,t}^{LES,in}) \geqslant 0 \tag{5.65}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{LES,in} \perp (\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,in}) \geqslant 0 \tag{5.66}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{LES,out} \perp (q_{i,\omega,t}^{LES,out}) \geqslant 0 \tag{5.67}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{LES,out} \perp (\overline{Q}_i^{LES} - q_{i,\omega,t}^{LES,out}) \geqslant 0 \tag{5.68}$$

$$0 \leqslant \underline{\mu}_{g,i,\omega,t}^{LES} \perp (g_{i,\omega,t}^{LES}) \geqslant 0 \tag{5.69}$$

$$0 \leqslant \overline{\mu}_{g,i,\omega,t}^{LES} \perp (\overline{G}_i^{LES} - g_{i,\omega,t}^{LES}) \geqslant 0 \tag{5.70}$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{CHP} \perp (w_{i,\omega,t}^{CHP}) \geqslant 0 \tag{5.71}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{CHP} \perp (\overline{W}_i^{CHP} - w_{i,\omega,t}^{CHP}) \geqslant 0 \tag{5.72}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{CHP} \perp (q_{i,\omega,t}^{CHP}) \geqslant 0 \tag{5.73}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{CHP} \perp (overlineQ_i^{CHP} - q_{i,\omega,t}^{CHP}) \geqslant 0 \tag{5.74}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{AB} \perp (q_{i,\omega,t}^{AB}) \geqslant 00 \leqslant \overline{\mu}_{h,i,\omega,t}^{AB} \perp (\overline{Q}_i^{AB} - q_{i,\omega,t}^{AB}) \geqslant 0 \tag{5.75}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS,in} \perp (q_{i,\omega,t}^{HS,in}) \geqslant 0 \tag{5.76}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS,in} \perp (\gamma_i^{HS} - q_{i,\omega,t}^{HS,in}) \geqslant 0 \tag{5.77}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS,out} \perp (q_{i,\omega,t}^{HS,out}) \geqslant 0 \tag{5.78}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS,out} \perp (\gamma_i^{HS} - q_{i,\omega,t}^{HS,out}) \geqslant 0 \tag{5.79}$$

$$0 \leqslant \underline{\mu}_{h,i,\omega,t}^{HS} \perp (q_{i,\omega,t}^{HS}) \geqslant 0 \tag{5.80}$$

$$0 \leqslant \overline{\mu}_{h,i,\omega,t}^{HS} \perp (\overline{Q}_i^{HS} - q_{i,\omega,t}^{HS}) \geqslant 0 \tag{5.81}$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{PV} \perp (w_{i,\omega,t}^{PV}) \geqslant 0 \tag{5.82}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{PV} \perp (overlineW_i^{PV,Forecast} - w_{i,\omega,t}^{PV}) \geqslant 0 \tag{5.83}$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{Wind} \perp (w_{i,\omega,t}^{Wind}) \geqslant 0 \tag{5.84}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{Wind} \perp (\overline{W}_i^{Wind,Forecast} - w_{i,\omega,t}^{Wind}) \geqslant 0 \tag{5.85}$$

$$0 \leqslant \underline{\mu}_{e,i,\omega,t}^{IL} \perp (w_{i,\omega,t}^{IL}) \geqslant 0 \tag{5.86}$$

$$0 \leqslant \overline{\mu}_{e,i,\omega,t}^{IL} \perp (\alpha_{i,t}^{IL} W_{i,t}^{MED} - w_{i,\omega,t}^{IL}) \geqslant 0 \tag{5.87}$$

Strong Duality:

$$
\begin{gathered}
\left((w_{i,\omega,t}^{LES,in} - w_{i,\omega,t}^{LES,out})\pi_{e,i,t}^{MEP} + g_{i,\omega,t}^{LES}\pi_{g,i,t}^{MEP} + (q_{i,\omega,t}^{LES,in} - q_{i,\omega,t}^{LES,out})\pi_{h,i,t}^{MEP}\right) \\
-\left((W_{i,t}^{MED} - W_{i,t}^{IL})\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\Pi_{h,i,t}^{MED} - W_{i,t}^{IL}\Pi_{i,t}^{IL,inc}\right) = \\
+\lambda_{e,i,t}^{MED}W_{i,t}^{MED} + \lambda_{g,i,t}^{MED}G_{i,t}^{MED} + \lambda_{h,i,t}^{MED}Q_{i,t}^{MED} \\
-0.5\lambda_{h,i,\omega,t}^{HS}Q_{i,\omega,t}^{HS}\Big|_{t=1} + \xi_{h,i,\omega,t}^{HS}\Big|_{t=1}Q_{i,\omega,t}^{HS}/2 + \xi_{h,i,\omega,t}^{HS}\Big|_{t=T}Q_{i,\omega,t}^{HS}/2 \\
-\overline{\mu}_{e,i,\omega,t}^{LES,in}\overline{W}_i^{LES} - \overline{\mu}_{e,i,\omega,t}^{LES,out}\overline{W}_i^{LES} - \overline{\mu}_{h,i,\omega,t}^{LES,in}\overline{Q}_i^{LES} - \overline{\mu}_{h,i,\omega,t}^{LES,out}\overline{Q}_i^{LES} \\
-\overline{\mu}_{g,i,\omega,t}^{LES}\overline{G}_i^{LES} - \overline{\mu}_{e,i,\omega,t}^{CHP}\overline{W}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{CHP}\overline{Q}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{AB}\overline{Q}_i^{AB} \\
-\overline{\mu}_{h,i,\omega,t}^{HS,in}\gamma_i^{HS}\overline{\mu}_{h,i,\omega,t}^{HS,out}\gamma_i^{HS} - \overline{\mu}_{h,i,\omega,t}^{HS}\overline{Q}_i^{HS} - \overline{\mu}_{e,i,\omega,t}^{PV}\overline{W}_i^{PV,Forecast} \\
-\overline{\mu}_{e,i,\omega,t}^{Wind}\overline{W}_i^{Wind,Forecast} - \overline{\mu}_{e,i,\omega,t}^{IL}\alpha_{i,t}^{IL}W_{i,t}^{MED}
\end{gathered} \tag{5.88}
$$

Detailed model of lower level problem is presented as follow:

Objective Function:

$$
\begin{gathered}
maximize\left\{f(x) = \sum_t \Bigg[- (w_t^{MEP}\Pi_{e,t}^{EM} + g_t^{MEP}\Pi_{g,t}^{GM}) \right. \\
+\sum_i \Bigg(+ \left((W_{i,t}^{MED} - W_{i,t}^{IL})\Pi_{e,i,t}^{MED} + G_{i,t}^{MED}\Pi_{g,i,t}^{MED} + Q_{i,t}^{MED}\Pi_{h,i,t}^{MED} - W_{i,t}^{IL}\Pi_{i,t}^{IL,inc}\right) \\
+\lambda_{e,i,t}^{MED}W_{i,t}^{MED} + \lambda_{g,i,t}^{MED}G_{i,t}^{MED} + \lambda_{h,i,t}^{MED}Q_{i,t}^{MED} \\
-0.5\lambda_{h,i,\omega,t}^{HS}Q_{i,\omega,t}^{HS}\Big|_{t=1} + \xi_{h,i,\omega,t}^{HS}\Big|_{t=1}Q_{i,\omega,t}^{HS}/2 + \xi_{h,i,\omega,t}^{HS}\Big|_{t=T}Q_{i,\omega,t}^{HS}/2 \\
-\overline{\mu}_{e,i,\omega,t}^{LES,in}\overline{W}_i^{LES} - \overline{\mu}_{e,i,\omega,t}^{LES,out}\overline{W}_i^{LES} - \overline{\mu}_{h,i,\omega,t}^{LES,in}\overline{Q}_i^{LES} - \overline{\mu}_{h,i,\omega,t}^{LES,out}\overline{Q}_i^{LES} \\
-\overline{\mu}_{g,i,\omega,t}^{LES}\overline{G}_i^{LES} - \overline{\mu}_{e,i,\omega,t}^{CHP}\overline{W}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{CHP}\overline{Q}_i^{CHP} - \overline{\mu}_{h,i,\omega,t}^{AB}\overline{Q}_i^{AB} \\
-\overline{\mu}_{h,i,\omega,t}^{HS,in}\gamma_i^{HS}\overline{\mu}_{h,i,\omega,t}^{HS,out}\gamma_i^{HS} - \overline{\mu}_{h,i,\omega,t}^{HS}\overline{Q}_i^{HS} - \overline{\mu}_{e,i,\omega,t}^{PV}\overline{W}_i^{PV,Forecast} \\
\left. -\overline{\mu}_{e,i,\omega,t}^{Wind}\overline{W}_i^{Wind,Forecast} - \overline{\mu}_{e,i,\omega,t}^{IL}\alpha_{i,t}^{IL}W_{i,t}^{MED} \Bigg] \right\}
\end{gathered} \tag{5.89}
$$

Constraints:

Primal optimal Condition: 5.2-5.6 and 5.10-5.34

Stationary Condition: 5.45-5.60

Complementary Condition: 5.61-5.87

5.4 Flexibility Assessment and Regulatory Framework

5.4.1 Flexibility Assessment

The main role of MES is enhancing the efficiency of energy system by utilizing all energy resources, simultaneously. Therefore, in this chapter the efficiency of MES to deliver required energy demand by utilizing various energy vectors is considered as the first flexibility index. In [] an efficiency index, namely fuel energy saving ratio (FESR) is proposed for CHP unit that considered the ratio of input energy quantity to the input ones. Equation 5.90 determines the same approach for LES that calculates the ratio of input energy carriers to deliver required energy of MED.

$$FESR_i = 1 - \sum_t \frac{1}{T}\left[\frac{\hat{w}_{i,t}^{LES} + \hat{q}_{i,t}^{LES} + \hat{g}_{i,t}^{LES}}{W_{i,t}^{MED} + Q_{i,t}^{MED} + G_{i,t}^{MED}}\right] \tag{5.90}$$

The second flexibility index is related to the capability of LES to utilize their internal energy resources instead of importing energy from upstream network. Equation 5.4.1 shows the general format to calculate this index for each energy carrier that will be deliver to MED. For energy converters the index is based on the share of output energy to the maximum capacity of energy converter in the study time horizon. On the other hand for energy storage the flexibility of energy storage to mitigate the variation of the system is considered as the variation of the normalized energy level of storage in consecutive time intervals.

$$\begin{gathered} LRUF_c = CUF_c + SUF_c = \\ \frac{1}{T(\alpha+\beta)}\left[\sum_\alpha \sum_t \frac{|E_{\alpha,c,t} - E_{\alpha,c,t-1}|}{\overline{E}_{\alpha,c}} + \sum_\beta \sum_t \frac{E_{\beta,c,t}}{\overline{E}_{\beta,c}}\right] \end{gathered} \tag{5.91}$$

5.4.2 Regulatory Frameworks

Three regulatory framework is considered in this chapter for aggregation of LES by MEP.

Centralized management for LES: In this aggregation mode MEP manages all the energy facilities of LES. This mode is related to the capability of MEP to have at least one way communication with LES to send the operation mode of each elements. Although, this mode needs vast communication infrastructure, it will reduce the planning cost for whole system by utilizing the synergy among LES. Equation (50) shows the objective function of MEP that operates whole system by utilizing LES facilities and interacting with energy market.

Pay as bid interaction of LES: In this mode MEP and each LES has equilibrium price for each energy carrier. The energy interaction of MEP and LES is represented 5.2.1.1-5.34.

Uniform pricing for LES: Despite of pay as bid framework, in this regulation mode all the LES received a same equilibrium price for each energy carrier. Therefore, instead of having various energy price for each LES (i.e. $\pi_{e,i,t}^{MEP}$, $\pi_{g,i,t}^{MEP}$, and $\pi_{h,i,t}^{MEP}$) we have the same energy price for all LES (i.e. $\pi_{e,t}^{MEP}$, $\pi_{g,t}^{MEP}$, and $\pi_{h,t}^{MEP}$).

5.5 Numerical Results

5.5.1 Input Data Characterization

In this chapter the MEP has three interior LES (5.2). It is assumed that MEP is a price taker player in energy market and its interaction with other energy players has no impact on the input energy prices. Therefore, its interaction with other energy players in energy market is based on the predetermined energy carriers' price signals (5.3). Data of electricity price for input of MEP have been obtained from the hourly data of the Spanish electricity market in May 2015 [19]. Moreover, LES interact energy with MEP and serve the energy to the MED. LES consist of CHP, AB, HS, IL, and RER. The comprehensive data for elements of these three LES are represented in Table 5.1. The MILP problem has been solved by CPLEX12 solver of GAMS package with an HP Z800 Workstation, CPU: 3.47 GHz, RAM: 96GB.

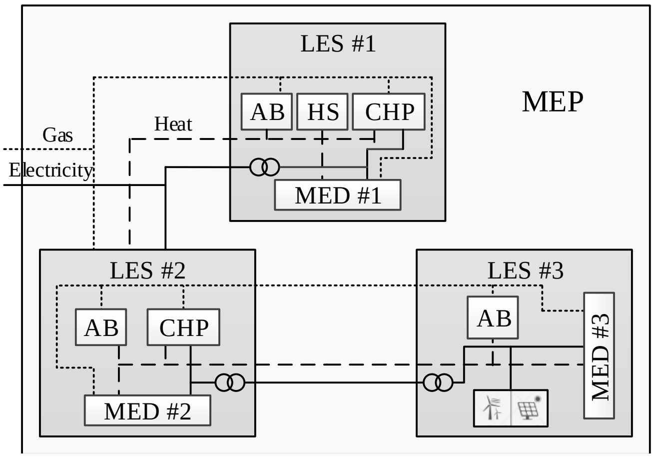

Figure 5.2: MEP and LES cooperation environment schematic.

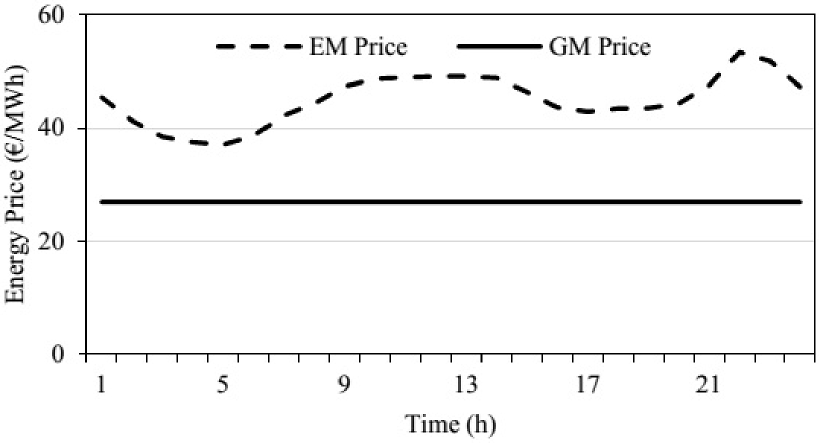

Figure 5.3: The hourly price of electricity and gas markets.

5.5.2 Regulatory Framework Evaluation

5.5.2.1 Case I: Centralized management for LES

Figure 5.4 and 5.5 demonstrate the electricity and heat balance for LES while MEP manage all facilities centrally. As it is shown, the main production of CHP units is during hours 9-13 and 17-21 while the electricity wholesale price is maximum and the MED have simultaneous consumption of electricity and heat. It should be noted

Table 5.1: Data of Local Energy System.

Elements		LES1	LES2	LES3
LES	Transformer	0.95	0.95	0.95
	Heat Pipelines Efficiency	0.9	0.9	0.9
CHP	Electricity Output	2.5 MW	1.5 MW	—
	Heat Output	3 MW	2.2 MW	—
	η_e^{CHP}, η_h^{CHP}	0.43, 0.35	0.45, 0.3	—
AB	Heat Output	2 MW	3 MW	1.5 MW
	η_h^{AB}	0.9	0.85	0.9
HS	Energy Capacity	3 MWh	—	—
	γ_h^{HS}	1.5 MW	—	—
	$\eta_h^{HS,cha}$, $\eta_h^{HS,dcha}$	0.9, 0.81	—	—
RER	Wind Capacity	—	—	3.3 MW
	PV Capacity	—	—	3.3 MW

that most of the time CHP units are in heat lead mode and produce electricity based on their heat demand and just in hours 22 and 23 CHP units are in electricity lead mode. In these hours the electricity price is very high but LES #1 doesn't have enough heat demand therefore the surplus heat production of CHP #1 has stored in HS #1 and CHP #1 can operate in electricity lead mode. Moreover, in hour 9-12 MEP can inject its electricity generation to the upstream network while the electricity price is almost high. In these hours the RER generation is maximum and high heat demand lead to minimum marginal cost for CHP units. Therefore, total marginal cost for electricity production of MEP will be lower than wholesale electricity market price.

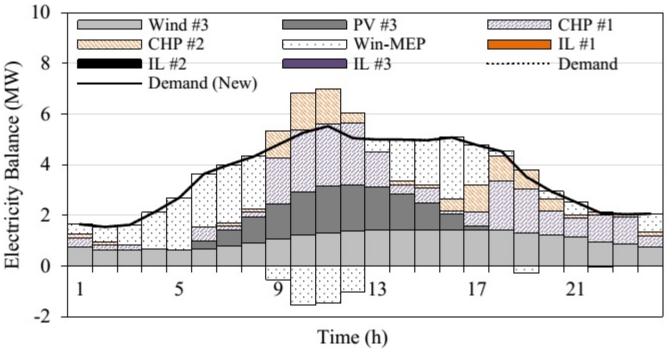

Figure 5.4: Share of each element in electricity energy balance of LES in Case I.

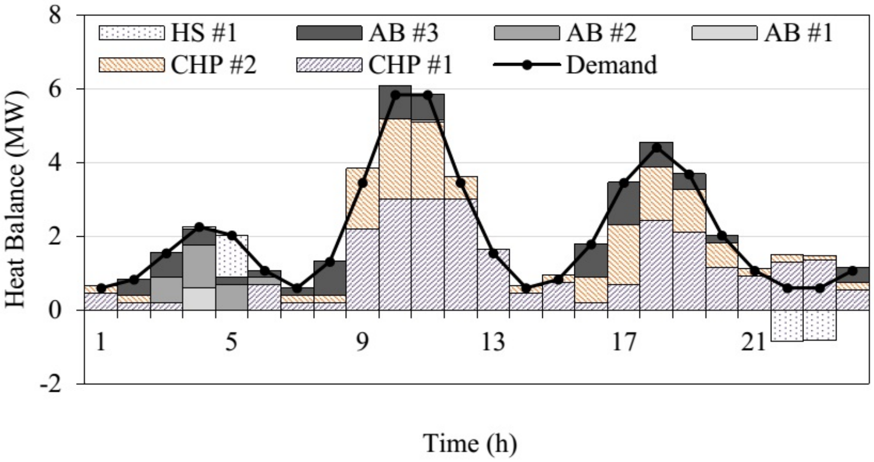

Figure 5.5: Share of each element in heat energy balance of LES in Case I.

5.5.2.2 Case II: Pay as bid interaction mode

In this mode MEP determines energy prices to interact with each LES. After that each LES schedules its heat and electricity balance. Figure 5.6 depicts equilibrium price for electricity, gas, and heat carriers in each LES. As it is shown MEP determine different energy price for each LES to maximize its profit by changing the behavior of each LES, independently. MEP is the only supplier of natural gas in the assumed system, therefore MEP increase the gas price in its price cap to maximize its profit. Moreover, high gas price lead to increase in the marginal cost of CHP units' electricity production.

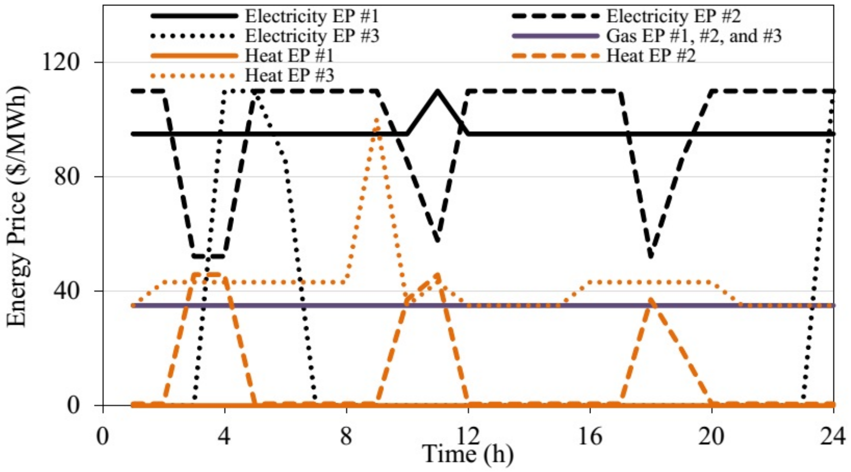

Figure 5.6: Electricity equilibrium price between MEP and LES in Case II.

For LES #1 that have HS, AB, and CHP unit and can satisfy its heat demand, MEP

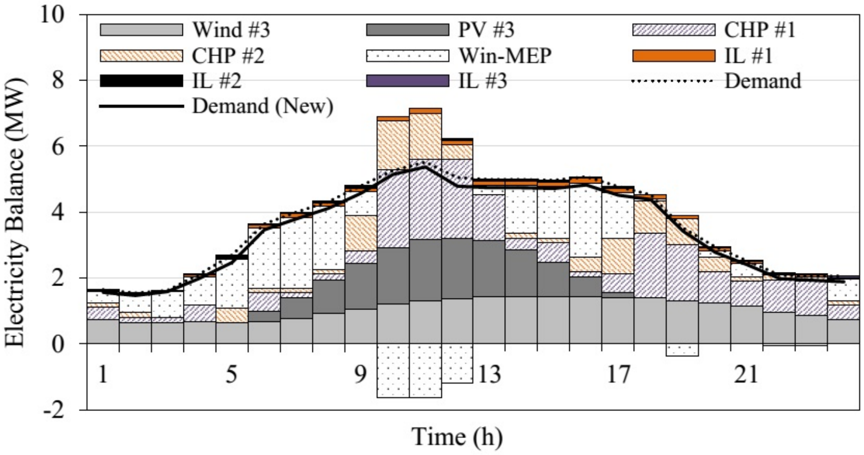

Figure 5.7: Share of each element in heat energy balance of LES in Case II.

maintains heat price in the lowest amount to prevent heat injection of LES #1 to other LES. Moreover, the equilibrium heat price is related to the capability of each LES to produce heat demand and is based on the marginal cost of heat production in LES.

The electricity price for each LES is related to the flexibility of LES to change its energy interaction with MEP. For LES #1 that have an efficient CHP unit, the electricity equilibrium price is almost equal to the marginal cost of CHP unit. Only in hour 11 while the price of electricity wholesale market is high, MEP increase the equilibrium price to the price cap to motivate LES #1 to increase its CHP units production to its maximum level. For LES #2, the efficiency of CHP unit is lower and therefore, the marginal cost of CHP unit production is low while the LES #2 has maximum heat demand. Therefore during the peak of heat demand in LES #2, the marginal cost of electricity production for LES #2 decrease and consequently the equilibrium electricity price is decreased, dramatically. For LES #3 with high penetration of RER, the marginal cost of electricity generation is very low therefore, in most of the hours the electricity equilibrium price is in the lowest amount for LES #3 . During hours 4-6 while the RER generation is very low and LES #3 has no more option to generate electricity, MEP increase the electricity price up to price cap to maximize its profit from selling energy to LES #3 .

5.5.2.3 Case III: Uniform pricing for LES

In this mode all LES schedule their energy balance based on a same equilibrium price. Figure 5.8 demonstrates equilibrium price for electricity, heat, and gas carriers. Due to same price for all LES in this case, the equilibrium is formed based on desire of all LES and has more variation. Similar to Case II, MEP is the only supplier of natural gas and increase the gas price up to price cap. The MEP aim to maximize its profit and has three main strategy to form the behavior of LES.

In the first strategy (e.g. hours 3, 4, and 13-16) MEP decrease the energy price to the marginal cost of CHP units to increase its market share and total profit. In the second one (e.g. hours 9-12), MEP decrease energy price and inject LES surplus energy to the upstream network and maximize its profit. In these hours due to high heat consumption and high RER production the marginal cost of electricity production for LES is low. Therefore, MEP can buy electricity in lower price from LES and sell it to the electricity market. Finally in the third strategy (e.g. hours 5-8), MEP increase the equilibrium price to maximize its profit through selling remaining LES energy need in maximum price.

It should be noted that, the profit of MEP is related to the energy content that MEP interact with other energy players and is independent from type of energy carrier. For instance, in this case during hours 9-12, MEP buy electricity from LES in higher price than electricity market and sell it to the electricity market. The key point is that LES generate electricity by utilizing CHP units and CHP units consume natural gas as primary resources. Therefore by generating more electricity by CHP units it means MEP sells more natural gas to the LES. Therefore, the net energy content that MEP is interacting with electricity wholesale market and LES is profitable.

5.5.3 Flexibility Assessment

Table 5.2 shows the amount of each flexibility indexes for three regulatory frameworks. The LES have two output to the MED, therefore, The *LURF* index has been calculated for both heat and electricity. As it is shown, the difference between centralized management mode and pay as bid interaction is negligible in all indexes.

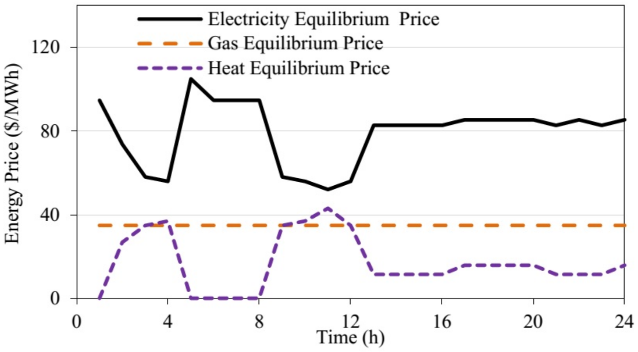

Figure 5.8: Electricity equilibrium price between MEP and LES in Case III.

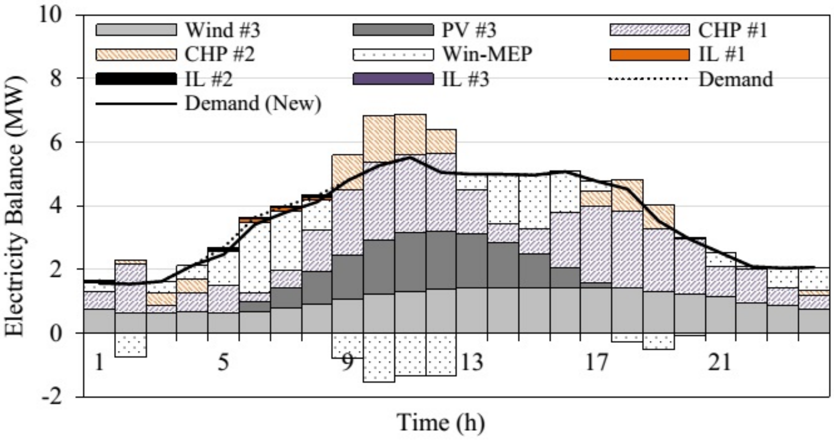

Figure 5.9: Share of each element in heat energy balance of LES in Case III.

As a matter of the fact in centralized management mode MEP can control all facilities of LES, directly and as the same in the pay as bid interaction mode, MEP send signal price to each LES, individually and can change the behavior of LES based on its desire. Although, the mechanism in these two modes are different to shape the behavior of LES, the final behavior of LES and especially the energy interaction of LES and MEP are the same. Moreover, in uniform pricing mode all flexibility indexes are higher than two other modes. In this mode $FESR$, is almost 4% more than pay as bid interaction mode. It ascertains that more competition in uniform pricing mode lead to interest of MEP to utilize the capability of LES to inject more energy to the upstream network Furthermore, $LRUF$ for heat has 11% and for electricity 34% increase from pay as bid to uniform pricing mode. As a matter of the fact, increasing the degree of freedom for decision making of LES result in more flexibility of LES to utilize their internal energy resources for both electricity and heat. The sharp increase in $LRUF_h$ is due to more utilization of CHP and HS units in uniform pricing to compare pay as bid interaction mode. Figure 5.10 depict the operational behavior of HS during 24 hours.

Table 5.2: Data of Flexibility Indexes.

	$FESR$	$LRUF_e$	$LRUF_h$
Centralized	0.882	0.272	0.254
Pay as Bid	0.882	0.272	0.255
Uniform Pricing	0.911	0.302	0.342

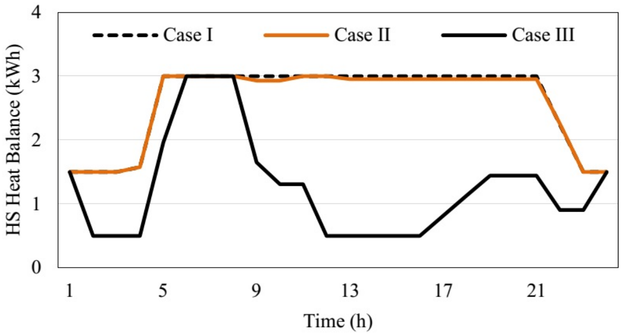

Figure 5.10: Comparison of CHP units operation in Case I, II, and III

5.6 Chapter Summary

The model of MEPs cooperation in the MESs has been developed in this chapter. Firstly, a fractal structure for MES has been proposed to consider MEPs' energy exchange and decision making conflicts. After that, the MEP and LES have been modeled, independently. The decision making conflicts among these players have been modeled through an MINLP bi-level approach. In the first level the MEP aims to maximize its profit and the equilibrium prices has been determined by cooperation of all LES. In the lower level each LES schedules its energy balance based on the equilibrium price and the energy exchange for each player will be concluded. For transforming the problem to a MILP single level problem, firstly the lower level problem has been replaced by its KKT optimality conditions. After that, based on the strong duality theorem, the objective function of the upper level problem has been linearized.

The numerical results show that the resource allocation of each LES determines its operational flexibility in short term and can explain its behavior to cooperate with other LES in a MES. Moreover, providing appropriate regulations in MES affect

MEP behavior and release hidden synergy among LES. For local energy carriers that produce and consume locally (i.e. heat), the variable marginal price motivates MEP to utilize their internal resources for maximizing their profit. On the other hand main energy carriers that cannot be generated locally (i.e. gas) should be regulated appropriately to mitigate market power of upper level MEP.

Chapter 6

Participation of Multi-Energy Players in Electricity Wholesale Market

6.1 Problem Statement

As described in chapter 3, the MES is considered as a multi-layer structure and consists of four layers, namely, energy market, multi-energy player (MEP), local energy system (LES), and multi-energy demand (MED). The multi-layer structure represents the behavior and scale of each energy player in the proposed MES. In order to investigate the impact of MEP on energy market performance, in this chapter a bi-level programming approach is implemented (figure 6.1). At the upper level, there is a MEP who is able to trade energy (electricity and natural gas) in energy markets and also with LES who serve exogenous demands for energy (electricity, natural gas, and heat) in their own areas. The objective of the MEP is to determine the optimal trading quantities in order to maximize its own profit subject to energy balance constraints. At the lower level, each LES acts as a prosumer that needs to decide the amount of each carriers to be provided either from the MEP or distributed resources. In addition to the energy balance constraints, each LES faces physical restrictions for the operation of installed equipment. Moreover, at the lower level, there are Gencos and retailers whose offers and bids are cleared by a welfare-maximizing independent system operator (ISO). The shadow price of the energy balance constraint of the ISO is the market-clearing price in the electricity market. Since each of the lower-level problems (ISO and LES) is convex, it may be replaced by its Karush–Kuhn–Tucker (KKT) conditions to turn the bi-level model into a mathematical programming with equilibrium constraints (MPEC). This is further simplified into an mixed-integer linear problem (MILP) by using disjunctive constraints and strong duality to resolve nonlinearities in the constraints and objective function of the MPEC. The numerical results show how market-clearing prices are affected by a greater penetration of MEP. However, overall energy production is more restricted to the local operations'

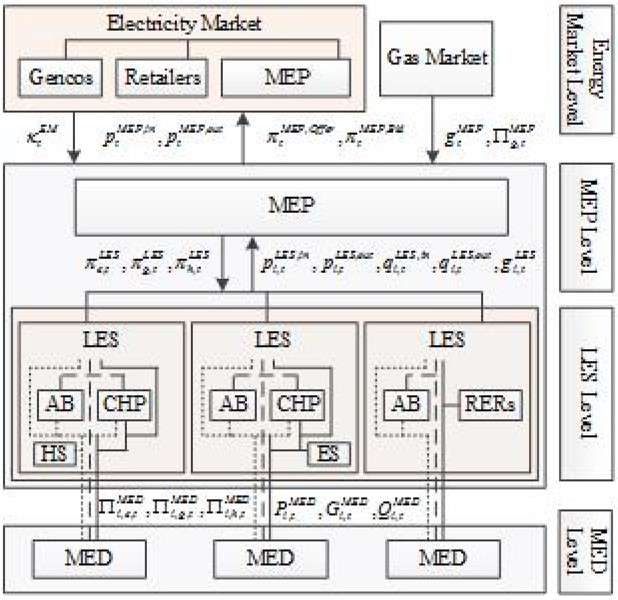

Figure 6.1: Interaction of MEP with LES and the wholesale electricity market.

considerations than to the wholesale electricity market price. The contributions of this chapter are as follows:

- Modeling the strategic behavior of an MEP in electricity wholesale market within a bi-level decision making problem;
- Considering the MEP as a medium to participate the demand side resources in the market in an aggregated manner for electricity, gas, and heat energy carriers and model its behavior through a bi-level decision making problem;
- Evaluating the impact of a high penetration of MEP on the equilibrium points of electricity wholesale market and the local aggregation of demand side energy resources and the cross impact of these two sets of equilibrium points.

6.2 The Mathematical Model for Decision Makers

In the proposed framework, MEP and LES are decision makers who decide about their energy interactions. MEP aggregates LES and interacts energy with the MEP based on the equilibrium price.

6.2.1 Multi-Energy Player's Decision Making Problem

The MEP purchases electricity from the electricity market at its market equilibrium price and natural gas from the gas market at a predetermined price. It also exchanges electricity, gas, and heat at the equilibrium price with LES. The objective function of the MEP is shown in (6.2.1). The first two terms are the costs of the MEP in the electricity and gas markets, respectively. The remaining terms are related to the incomes of the MEP in distribution level from trading electricity, gas and heat with LES at the energy equilibrium prices. Therefore, decision vector of MEP for aggregation of LES is $[\pi_{e,t}^{MEP}, \pi_{g,t}^{MEP}, \pi_{h,t}^{MEP}]$.

$$maximize \Bigg\{ f(x) = \sum_t \Bigg[-(p_t^{MEP,in} - p_t^{MEP,out})\kappa_t^{EM} - g_t^{MEP}\pi_{g,t}^{MEP}$$
$$+ \sum_i \Big((p_{i,t}^{LES,in} - p_{i,t}^{LES,out})\pi_{e,i,t}^{Agg} + g_{i,t}^{LES}\pi_{g,i,t}^{Agg} + (q_{i,t}^{LES,in} - q_{i,t}^{LES,out})\pi_{h,i,t}^{Agg} \Big) \Bigg] \Bigg\}$$

The operational constraints of MEP decision making problem have been represented in Chapter 5 (equations 5.2-5.6).

6.2.2 Local Energy Systems' Decision Making Problem

LES is equipped with combined heat and power (CHP) unit, auxiliary boiler (AB), heat storage (HS), RER, and electric storage (ES). Each LES trades at equilibrium prices with the MEP and deliver the required services to MED to maximize its profit (6.2.2). The first three terms of the LES objective function determine the incomes from the energy sold (electricity, gas and heat) to MED. The remaining terms are similar to the ones of the MEP, the costs from trading energy with the MEP in the aggregation equilibrium price. These terms are the coupling variables between MEP and LES. The decision vector of LES is $[p_{i,t}^{LES,in}, p_{i,t}^{LES,out}, q_{i,t}^{LES,in}, q_{i,t}^{LES,out}, g_{i,t}^{LES}]$.

$$maximize\Bigg\{ g_i(x_i) = \sum_t \Bigg[P_{i,t}^{MED}\Pi_{e,i,t}^{MEP} + G_{i,t}^{MED}\Pi_{g,i,t}^{MEP} + Q_{i,t}^{MED}\Pi_{h,i,t}^{MEP}$$

$$- \sum_i \Big((p_{i,t}^{LES,in} - p_{i,t}^{LES,out})\pi_{e,i,t}^{Agg} - g_{i,t}^{LES}\pi_{g,i,t}^{Agg} - (q_{i,t}^{LES,in} - q_{i,t}^{LES,out})\pi_{h,i,t}^{Agg} \Big) \Bigg] \Bigg\} \tag{6.1}$$

The LES operational constraints are based on the equations 5.2.2.2-5.32 in Chapter 4.

6.3 MPEC Formulation of The Local Decision Making Problem

The MEP's decision making process as the aggregated form of LES resources may result in different outcomes rather than the individually operation of each LES. As a result, in this study a bilevel problem is considered where on the lower level the aggregated operation of LESs is considered and on the upper level the MEP interaction with the market is formulated. To transform the bi-level problem into a single-level MILP problem, we use MPEC ([106] and [104]). The proposed procedure is as follows:

- Transforming the lower-level problem into a convex and linear one;
- Replacing the lower-level problem with its KKT optimality conditions;
- Applying the strong duality theorem to linearize the non-linear terms of the upper-level problem.

The mathematical model of LES problem is convex and linear; therefore, in 6.2 it is shown that the Lagrangian of the LES problem and 6.3-6.6 are its KKT optimality conditions. Equations 6.3-6.6 are the stationary conditions, the primal optimality conditions and the complementarity conditions for the lower-level problem. The linearized form of 6.6 and the upper-level objective function are explained in Appendix

A.

$$\mathcal{L}_i^{LES} = \mathbf{g_i}(\mathbf{X_i}) - \mu_\mathbf{i}^\mathbf{LES}\mathbf{N}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) + \lambda_\mathbf{i}^\mathbf{LES}\mathbf{E}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) + \xi_\mathbf{i}^\mathbf{LES}\mathbf{T}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) \tag{6.2}$$

$$\partial\mathcal{L}_i^{LES}/\partial\mathbf{X_i} = \mathbf{0} \tag{6.3}$$

$$\partial\mathcal{L}_i^{LES}/\partial\lambda_\mathbf{i}^\mathbf{LES} = \mathbf{E}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) = \mathbf{0} \tag{6.4}$$

$$\partial\mathcal{L}_i^{LES}/\partial\xi_\mathbf{i}^\mathbf{LES} = \mathbf{T}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) = \mathbf{0} \tag{6.5}$$

$$0 \leq \mu_\mathbf{i}^\mathbf{LES} \perp \mathbf{N}_\mathbf{i}^\mathbf{LES}(\mathbf{X_i}) \geq \mathbf{0} \tag{6.6}$$

6.4 Mathematical Formulation of The Electricity Market

The MEP is a strategic player that competes with other players in an electricity market environment. This behavior is modeled using bi-level optimization, where the MEP resolves its strategy in the upper level and the impact of its decision on electricity market parameters is determined in the lower level. In the lower level, the ISO receives the market players bids/offers and clears the market to maximize social welfare 6.7. The first two terms of this equation are the offers and bids of the MEP as a simultaneous electricity producer and consumer. The next two terms are the other electricity market players' strategies that consist of the Gencos' offers and the retailers' bids. The decision vector of MEP is $[\pi_t^{MEP,Bid}, \pi_t^{MEP,Offer}]$ and the decision vector of lower level problem is $[p_{j,t}^{Retailer}, p_{k,t}^{Genco}, p_t^{MEP,out}, p_t^{MEP,in}]$.

$$maximize\left\{ h(x) = \sum_t \left[p_t^{MEP,in}\pi_t^{MEP,Bid} - p_t^{MEP,out}\pi_t^{MEP,Offer} \right.\right. \tag{6.7}$$

$$\left.\left. + \sum_j p_{j,t}^{Retailer}\Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco}\Pi_{k,t}^{Genco,Offer} \right] \right\} \tag{6.8}$$

The power balance of the electricity market is shown in 6.9. The dual variable of this equation is the market clearing price. In addition, 6.10-6.13 show the upper limits of generation/demand, which are equal to the offers/bids.

$$-\sum_{k} p_{k,t}^{Genco} + \sum_{j} p_{j,t}^{Retailer} - p_t^{MEP,out} + p_t^{MEP,in} = 0 \ : \kappa_t^{EM} \tag{6.9}$$

$$N_{k,t}^{EM,1}, N_{k,t}^{EM,2} : 0 \leq p_{k,t}^{Genco} \leq \overline{P}_k^{Genco} \qquad : \underline{\mu}_{k,t}^{Genco}, \overline{\mu}_{k,t}^{Genco} \tag{6.10}$$

$$N_{j,t}^{EM,3}, N_{j,t}^{EM,4} : 0 \leq p_{j,t}^{Retailer} \leq \overline{P}_j^{Retailer} \quad : \underline{\mu}_{j,t}^{Retailer}, \overline{\mu}_{j,t}^{Retailer} \tag{6.11}$$

$$N_t^{EM,5}, N_t^{EM,6} : 0 \leq p_t^{MEP,in} \leq \overline{P}^{MEP} \qquad : \underline{\mu}_t^{MEP,in}, \overline{\mu}_t^{MEP,in} \tag{6.12}$$

$$N_t^{EM,7}, N_t^{EM,8} : 0 \leq p_t^{MEP,out} \leq \overline{P}^{MEP} \quad : \underline{\mu}_t^{MEP,out}, \overline{\mu}_t^{MEP,out} \tag{6.13}$$

6.4.1 Comprehensive Model of KKT Condition for The Electricity Market

Equations 6.7-6.13 represent another lower-level problem of the MEP, in this case related to the electricity market behavior. The procedure for converting this bi-level problem is the same as the one in the previous chapter. Equation 6.14 shows the Lagrangian of the lower-level problem. Equations 6.15-6.17 are the stationary conditions, primal optimality conditions and the complementarity conditions of the electricity market problem.

$$\mathcal{L}^{EM} = \mathbf{h}(\mathbf{X}) - \mu^{\mathbf{EM}}\mathbf{N}^{\mathbf{EM}}(\mathbf{X}) + \lambda^{\mathbf{EM}}\mathbf{E}^{\mathbf{EM}}(\mathbf{X}) \tag{6.14}$$

$$\partial\mathcal{L}^{EM}/\partial\mathbf{X} = \mathbf{0} \tag{6.15}$$

$$\partial\mathcal{L}^{EM}/\partial\lambda^{\mathbf{EM}} = \mathbf{E}^{\mathbf{EM}}(\mathbf{X}) = \mathbf{0} \tag{6.16}$$

$$0 \leq \mu^{\mathbf{EM}} \perp \mathbf{N}^{\mathbf{EM}}(\mathbf{X}) \geq \mathbf{0} \tag{6.17}$$

After transforming the electricity market level, the three-level optimization problem is converted into a single-level MILP problem whose objective function is given in 6.2.1 after linearizing the non-linear terms, with the set of constraints 6.2.2-6.4, 6.3-6.6, and 6.15-6.17.

6.4.2 Detailed Model of KKT Condition for The Electricity Market

Based on the comprehensive model description, the lagrangian expression, complementary, and stationary conditions of lower level problem are represented as follow, respectively.

Lagrangian Expression:

$$\begin{aligned}\mathcal{L}^{EM} = -\Big[& p_t^{MEP,in}\pi_t^{MEP,Bid} - p_t^{MEP,out}\pi_t^{MEP,Offer} \\ & + \sum_j p_{j,t}^{Retailer}\Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco}\Pi_{k,t}^{Genco,Offer}\Big] \\ & + \kappa_t^{EM}(-\sum_k p_{k,t}^{Genco} + \sum_j p_{j,t}^{Retailer} - p_t^{MEP,out} + p_t^{MEP,in}) \\ & - \underline{\mu}_{k,t}^{Genco}(p_{k,t}^{Genco}) - \overline{\mu}_{k,t}^{Genco}(\overline{P}_k^{Genco} - p_{k,t}^{Genco}) \\ & - \underline{\mu}_{j,t}^{Retailer}(p_{j,t}^{Retailer}) - \overline{\mu}_{j,t}^{Retailer}(\overline{P}_j^{Retailer} - p_{j,t}^{Retailer}) \\ & - \underline{\mu}_t^{MEP,in}(p_t^{MEP,in}) - \overline{\mu}_t^{MEP,in}(\overline{P}^{MEP} - p_t^{MEP,in}) \\ & - \underline{\mu}_t^{MEP,out}(p_t^{MEP,out}) - \overline{\mu}_t^{MEP,out}(\overline{P}^{MEP} - p_t^{MEP,out})\end{aligned} \tag{6.18}$$

Stationary Condition:

$$\partial\mathcal{L}^{EM}/\partial p_t^{MEP,in} = -\pi_t^{MEP,Bid} + \kappa_t^{EM} - \underline{\mu}_t^{MEP,in} + \overline{\mu}_t^{MEP,in} = 0 \tag{6.19}$$

$$\partial\mathcal{L}^{EM}/\partial p_t^{MEP,out} = +\pi_t^{MEP,offer} - \kappa_t^{EM} - \underline{\mu}_t^{MEP,out} + \overline{\mu}_t^{MEP,out} = 0 \tag{6.20}$$

$$\partial\mathcal{L}^{EM}/\partial p_{j,t}^{Retailer} = -\Pi_{j,t}^{Retailer,Bid} + \kappa_t^{EM} - \underline{\mu}_{j,t}^{Retailer} + \overline{\mu}_{j,t}^{Retailer} = 0 \tag{6.21}$$

$$\partial\mathcal{L}^{EM}/\partial p_{k,t}^{Genco} = +\Pi_{k,t}^{Genco,Offer} - \kappa_t^{EM} - \underline{\mu}_{k,t}^{Genco} - \overline{\mu}_{k,t}^{Genco} = 0 \tag{6.22}$$

Complementary Condition:

$$0 \leqslant \underline{\mu}_{k,t}^{Genco} \perp (p_{k,t}^{Genco}) \geqslant 0 \tag{6.23}$$

$$0 \leqslant \overline{\mu}_{k,t}^{Genco} \perp (\overline{P}_{k}^{Genco} - p_{k,t}^{Genco}) \geqslant 0 \tag{6.24}$$

$$0 \leqslant \underline{\mu}_{j,t}^{Retailer} \perp (p_{j,t}^{Retailer}) \geqslant 0 \tag{6.25}$$

$$0 \leqslant \overline{\mu}_{j,t}^{Retailer} \perp (\overline{P}_{j}^{Retailer} - p_{j,t}^{Retailer}) \geqslant 0 \tag{6.26}$$

$$0 \leqslant \underline{\mu}_{t}^{MEP,in} \perp (p_{t}^{MEP,in}) \geqslant 0 \tag{6.27}$$

$$0 \leqslant \overline{\mu}_{t}^{MEP,in} \perp (\overline{P}^{MEP} - p_{t}^{MEP,in}) \geqslant 0 \tag{6.28}$$

$$0 \leqslant \underline{\mu}_{t}^{MEP,out} \perp (p_{t}^{MEP,out}) \geqslant 0 \tag{6.29}$$

$$0 \leqslant \overline{\mu}_{t}^{MEP,out} \perp (\overline{P}^{MEP} - p_{t}^{MEP,out}) \geqslant 0 \tag{6.30}$$

6.4.3 Objective Function Linearization

In order to linearize the objective function, strong duality theory is applied. The strong duality condition states that the gap between the primal and dual optimal values is approximately zero at optimality and the primal and dual objective functions can be equal. At the electricity market level, equation 6.31 shows the strong duality condition for linearizing $p_t^{MEP,in}\kappa_t^{EM}$ and $p_t^{MEP,out}\kappa_t^{EM}$ in the MEP objective function.

$$\begin{aligned} -\Bigg[& p_t^{MEP,in}\pi_t^{MEP,Bid} - p_t^{MEP,out}\pi_t^{MEP,Offer} \\ & + \sum_j p_{j,t}^{Retailer}\Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco}\Pi_{k,t}^{Genco,Offer}\Bigg] = \\ & - \sum_k \overline{\mu}_{k,t}^{Genco}\overline{P}_k^{Genco} - \sum_j \overline{\mu}_{j,t}^{Retailer}\overline{P}_j^{Retailer} \\ & - \overline{\mu}_t^{MEP,in}\overline{P}^{MEP} - \overline{\mu}_t^{MEP,out}\overline{P}^{MEP} \end{aligned} \tag{6.31}$$

From the KKT conditions we have equations 6.32 and 6.33 for calculating the amount of $\pi_t^{MEP,Offer}$ and $\pi_t^{MEP,Bid}$.

$$\pi_t^{MEP,Bid} = \kappa_t^{EM} - \underline{\mu}_t^{MEP,in} + \overline{\mu}_t^{MEP,in} = 0 \tag{6.32}$$

$$\pi_t^{MEP,offer} = \kappa_t^{EM} + \underline{\mu}_t^{MEP,out} - \overline{\mu}_t^{MEP,out} = 0 \tag{6.33}$$

Multiplying equalities 6.32 and 6.33 by MEP production variables $p_t^{MEP,in}$ and $p_t^{MEP,out}$, respectively, renders the equalities below:

$$\begin{gathered}
-\Big[p_t^{MEP,in}(\kappa_t^{EM} - \underline{\mu}_t^{MEP,in} + \overline{\mu}_t^{MEP,in}) - p_t^{MEP,out}(\kappa_t^{EM} + \underline{\mu}_t^{MEP,out} - \overline{\mu}_t^{MEP,out}) \\
+ \sum_j p_{j,t}^{Retailer} \Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco} \Pi_{k,t}^{Genco,Offer}\Big] = \\
- \sum_k \overline{\mu}_{k,t}^{Genco} \overline{P}_k^{Genco} - \sum_j \overline{\mu}_{j,t}^{Retailer} \overline{P}_j^{Retailer} \\
- \overline{\mu}_t^{MEP,in} \overline{P}^{MEP} - \overline{\mu}_t^{MEP,out} \overline{P}^{MEP}
\end{gathered} \tag{6.34}$$

$$\begin{gathered}
-p_t^{MEP,in} \kappa_t^{EM} + p_t^{MEP,out} \kappa_t^{EM} = \\
+p_t^{MEP,in}(-\underline{\mu}_t^{MEP,in} + \overline{\mu}_t^{MEP,in}) - p_t^{MEP,out}(+\underline{\mu}_t^{MEP,out} - \overline{\mu}_t^{MEP,out}) \\
+ \sum_j p_{j,t}^{Retailer} \Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco} \Pi_{k,t}^{Genco,Offer} \\
- \sum_k \overline{\mu}_{k,t}^{Genco} \overline{P}_k^{Genco} - \sum_j \overline{\mu}_{j,t}^{Retailer} \overline{P}_j^{Retailer} \\
- \overline{\mu}_t^{MEP,in} \overline{P}^{MEP} - \overline{\mu}_t^{MEP,out} \overline{P}^{MEP}
\end{gathered} \tag{6.35}$$

On the other hand, from complementarity conditions we have the equations 6.36 - 6.39:

$$\underline{\mu}_t^{MEP,in} p_t^{MEP,in} = 0 \tag{6.36}$$

$$\overline{\mu}_t^{MEP,in}(\overline{P}^{MEP} - p_t^{MEP,in}) = 0 \Rightarrow \overline{\mu}_t^{MEP,in} p_t^{MEP,in} = \overline{\mu}_t^{MEP,in} \overline{P}^{MEP} \tag{6.37}$$

$$\underline{\mu}_t^{MEP,out} p_t^{MEP,out} = 0 \tag{6.38}$$

$$\overline{\mu}_t^{MEP,out}(\overline{P}^{MEP} - p_t^{MEP,out}) = 0 \Rightarrow \overline{\mu}_t^{MEP,out} p_t^{MEP,out} = \overline{\mu}_t^{MEP,out} \overline{P}^{MEP} \tag{6.39}$$

Substituting 6.36 - 6.39 in the equation 6.35 renders the equality below:

$$\begin{aligned}\kappa_t^{EM}(p_t^{MEP,out} - p_t^{MEP,in}) = \overline{\mu}_t^{MEP,in}\overline{P}^{MEP} + \overline{\mu}_t^{MEP,out}\overline{P}^{MEP} \\ + \sum_j p_{j,t}^{Retailer}\Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco}\Pi_{k,t}^{Genco,Offer} \\ - \sum_k \overline{\mu}_{k,t}^{Genco}\overline{P}_k^{Genco} - \sum_j \overline{\mu}_{j,t}^{Retailer}\overline{P}_j^{Retailer} - \overline{\mu}_t^{MEP,in}\overline{P}^{MEP} - \overline{\mu}_t^{MEP,out}\overline{P}^{MEP} = \\ \sum_j p_{j,t}^{Retailer}\Pi_{j,t}^{Retailer,Bid} - \sum_k p_{k,t}^{Genco}\Pi_{k,t}^{Genco,Offer} - \sum_k \overline{\mu}_{k,t}^{Genco}\overline{P}_k^{Genco} - \sum_j \overline{\mu}_{j,t}^{Retailer}\overline{P}_j^{Retailer}\end{aligned} \tag{6.40}$$

6.5 Numerical Results

In the numerical results the behavior of MEP to interact with LES and its participation in wholesale electricity market is investigated. The model have been solved by CPLEX 10 on HP Z800 workstation with CPU: 3.47 GHz and RAM: 96 GB .

6.5.1 Input Data Characterization

The MEP aggregates three LES inside and competes with 10 Gencos and 10 retailers in the electricity market. Table 6.1 shows the input data for the LES. Table 6.2 contains the bids and offers of the electricity market players. For all the retailers, the offering steps are considered the same as in the base case, where α_t is a correction factor to create the bidding steps 6.41 changing the amount of the retailers' bidding in each hour.

$$p_{j,t}^{Retailer} = \alpha_t \left(p_{j,t}^{Retailer,base}\right) \tag{6.41}$$

The gas market price is considered as \$25/MWh. Furthermore, to avoid price spikes in the local energy market, the price caps for electricity, gas and heat are \$130/MWh, \$150/MWh, and \$40/MWh, respectively. In addition, Fig. 6.3 depicts the total energy consumption of MED.

Table 6.1: Data of Local Energy System.

Elements		**LES1**	**LES2**	**LES3**
LES	Transformer	0.95	0.95	0.95
	Heat Pipelines Efficiency	0.9	0.9	0.9
CHP	Electricity Output	25 MW	15 MW	—
	Heat Output	30 MW	22 MW	—
	η_e^{CHP}, η_h^{CHP}	0.45, 0.35	0.47, 0.3	—
AB	Heat Output	20 MW	30 MW	15 MW
	η_h^{AB}	0.9	0.85	0.9
HS	Energy Capacity	30 MWh	—	—
	γ_h^{HS}	15 MW	—	—
	$\eta_h^{HS,cha}$, $\eta_h^{HS,dcha}$	0.81, 0.9	—	—
ES	Capacity	—	20 MWh	—
	γ_h^{ES}	—	10 MW	—
	$\eta_h^{ES,cha}$, $\eta_h^{ES,dcha}$	0.81, 0.9	0.81, 0.9	—
RER	Wind Capacity	—	—	30 MW
	PV Capacity	—	—	30 MW

Table 6.2: Electricity Market Players Data

Genco No.	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
Type	Oil	Oil	Oil	Hydro	Coal	Oil	Coal	Oil	Coal	Nuclear
Unit Number	10	6	5	6	4	3	4	3	1	2
$\overline{P}_k^{Genco}[MW]$	12	20	30	50	75	100	155	197	350	400
Marginal Cost [$/MWh]	40	40	65	0	23	35	20	33	19	8

Retailer No.	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
$\overline{P}_j^{Retailer}[MW]$	250	250	250	250	250	250	250	250	250	250
Utility Function [$/MWh]	75	70	65	60	57	53	50	50	45	40

6.5.2 Equilibrium Price for the Aggregation of LES

Figure 6.4 shows the energy carrier prices for the LES and electricity market clearing prices. As shown, due to the small energy exchange of the MEP, it is a price taker in the electricity market and the market price is solely determined based on Gencos' and retailers' offers and bids, respectively. Figures 6.5 and 6.6 show the power and heat balance of the MEP, respectively. MEP trades three types of energy carriers that their behaviors are as follows:

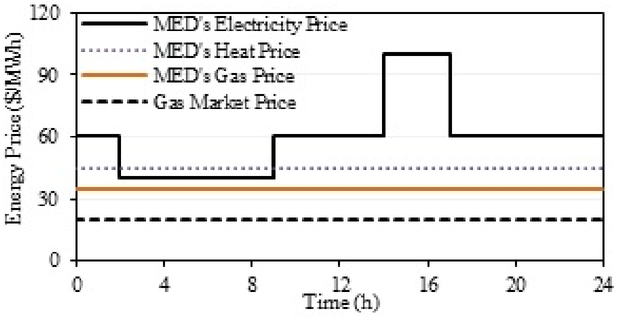

Figure 6.2: MED time of use tariff and gas market hourly prices.

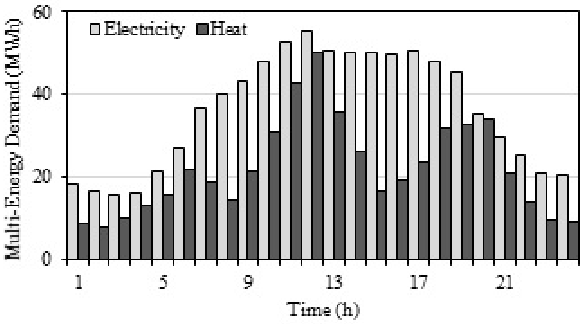

Figure 6.3: Total consumption of MED in the local energy system.

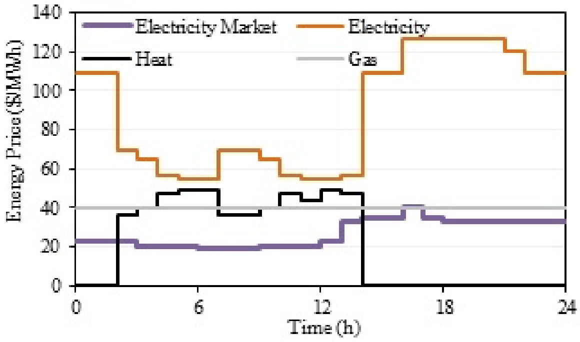

Figure 6.4: Energy carrier prices in the local energy market and clearing prices of the electricity market.

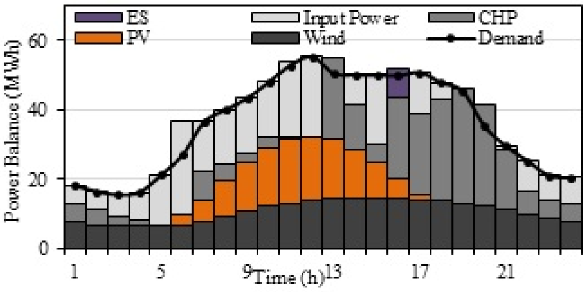

Figure 6.5: Share of LES energy resources for MEP electricity balance.

6.5.2.1 Natural gas

Natural gas is a grid-bounded carrier that cannot be produced locally and the MEP delivers the required amount to LES. Therefore, its price always is equal to the price cap and the MEP maximizes its profit by maximizing the gas price.

6.5.2.2 Heat

Heat is a local energy carrier and is produced only by AB and CHP units. Therefore, its price depends on local operational considerations. In hours 2-13, while the heat production of CHP units does not satisfy MED's needs and the LES use their AB (CHP units are in heat-lead mode), the heat price is equal to the marginal cost of the AB. On the other hand, after hour 13, while the price of electricity is high and the CHP units are in electricity-lead mode, the price of heat is almost equal to zero and heat will be produced as a supplementary good when generating electricity in the CHP units. As a matter of fact, producing heat is like a bonus for LES helping them to operate their CHP units within their operational limits.

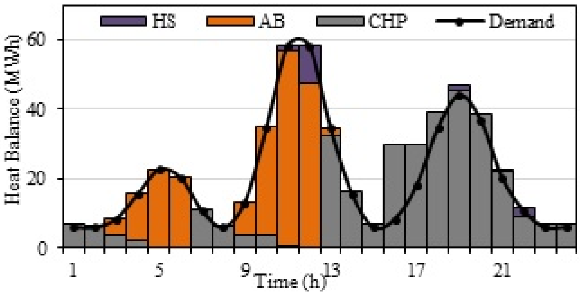

Figure 6.6: Share of LES energy resources for MEP heat balance.

6.5.2.3 Electricity

Electricity can be generated locally or delivered by the MEP. The electricity price has the same behavior as the electricity market price. Note that the aggregator's equilibrium price of electricity depends on the capability of CHP units to produce cheaper electricity. In general, the electricity price of the CHP units is high but when LES have large simultaneous heat and electricity demands, their generation will be profitable. However, as these units increase their level of electricity generation, their vacant capacity to compete in the local market will decrease. Therefore, the MEP will increase the electricity price to maximize its profit. The profit of the MEP depends on two factors: energy quantity and energy price. In the first period (hours 1-13), the MEP increases its profit by decreasing the local electricity price, forcing the CHP units to decrease their generation to increase its own energy delivery share. On the contrary, in the second period (14-24), while the marginal cost of the CHP unit is low, it prefers to increase the electricity price up to the price cap, maximizing its profit by selling electricity to the remaining MED at the highest possible price.

6.5.3 Impact of a High Penetration of MEP

Figure 6.7 depicts the impact of a high penetration of MEP on the electricity market. In this chapter, the penetration rate of the MEP is defined as the share of the MEP electricity demand with respect to the total demand of the system.

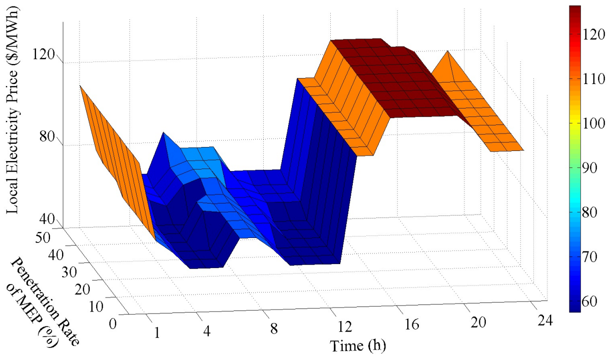

Figure 6.7: Impact of increasing the penetration rate of MEP on market prices.

As shown, by increasing the share of MEP, electricity prices will increase in most periods (hours 1-10 and 13-19). However, in hour 11, with a penetration of more than 35%, electricity price will decrease. In this hour, the MEP injects its electricity surplus to the grid. Figures 6.8 and 6.9 depict the electricity and heat equilibrium prices for the aggregation of LES for various penetration rates of MEP, respectively. By increasing the electricity market price, the equilibrium electricity price increases and motivates LES to use their internal resources (CHP units and ES) to locally generate electricity. Therefore, the price of heat as a supplementary production in the CHP process decreases in the corresponding hours.

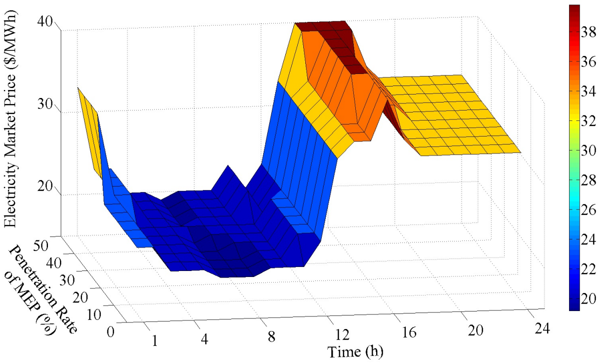

Figure 6.8: Impact of increasing the penetration rate of MEP on aggregator's electricity price.

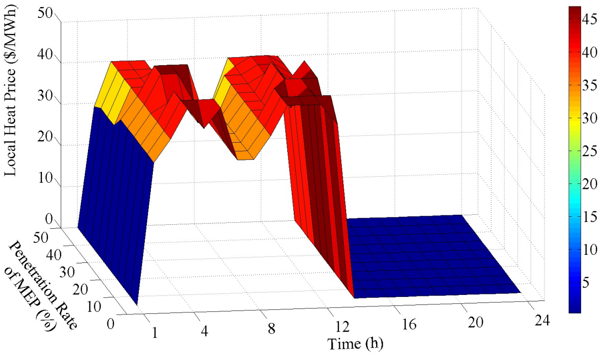

Figure 6.9: Impact of increasing the penetration rate of MEP on aggregator's heat price.

Note that, in general, the MEP's strategy assures the adequacy of generation by using local energy resources, however, it should be noted that these resources are affected by the local operational constraints and their operation is correlated to their state of local management. For instance, the electricity production of CHP units and its marginal cost is related to the heat consumption of the MED. Although in case of a contingency these local resources can protect the system and increase reliability indices, in a normal operation the local constraints determine their capability to rival with the other market players. Therefore, in comparison with bulk generation, these resources are not beneficial at all times.

Moreover, their marginal costs are not only related to their levels of production but also dependent to their local operational considerations, and are varying in operation time horizon. In the case studied, the lowest marginal cost for CHP production is during hours 11-13, while the MEP has the maximum heat consumption, but the system peak occurs between hours 14-17.

6.6 Chapter Summary

In this chapter, the behavior of an MEP was investigated for a simultaneous behavior to aggregate a set of LES and participate in the wholesale electricity markets. Moreover, the impacts of a high penetration of MEP on these two sets of equilibrium prices were studied. Numerical results showed that local energy price equilibrium was related to the local energy resources of LES. Due to the mutual dependency of the energy carriers, LES may have variable marginal costs for the energy production in the operation period. This time-based marginal cost affected local market parameters and, if the penetration rates of MEP increase, it can affect them. Although the changes in the electricity market price may be small, they affected the strategy of the other electricity market players. MEP increased the total efficiency of the system, but it does not mean that they can decrease the price or the demand in the peak hour. The energy produced by the MEP was more related to local operational considerations, rather than the electricity market price.

Chapter 7

Conclusion and Future Research

7.1 Conclusion

The conclusion remarks of this research can be categorized and presented as the following:

- Based on research outlines, it can be concluded that the capability of MEPs for interaction and development depends on their local energy resources. Furthermore, this capability is different from one carrier to another, and depends on the flexibility of the players in the production and consumption of that carrier. However, there might be a passive relation between the carriers as a results of their interdependency. In the conducted studies, carriers of electricity, gas and heat had different conditions in production and consumption. Production of energy carrier in large scales and receiving it from transmission levels, the changes in the price of this carrier in local energy carriers have been father intensified. These price changes determine the strategy of MEPs to utilize their local energy resources.
- Due to emerging of new technologies, the flexibility of MEP has also been altered. Each local energy resources can enhance the flexibility of these players. Therefore, the behavior of MEPs and their energy exchange in local layers depends on the flexibility of these players to substitute the energy consumption between energy carriers. In this condition the total profit of MEPs is considered base on net energy exchange beyond the type of interacted energy carriers. Hence, in the proposed case studies the necessity to sell gas as a primary energy resource along electricity is highlighted for MEPs. The numerical results show, in some case studies the electricity may be purchased with higher prices from LES, but the sold gas volume guarantee the positive

profit of MEPs. This strategy, motivates LESs to utilize their gas-based local energy resources that have a simultaneous benefit for both LES and MEP.

- Due to capability of MEPs to produce and consume energy, simultaneously, they can influence on the price of electricity carrier in wholesale markets. Moreover, based on the iterdependency of energy carriers, the MEPs marginal cost is variable in the operation time horizon. Moreover, the dual behavior of MEPs as producer and consumers brings flexibility to whole system to fill market demand valleys by MEPs consumption and shave its peak with MEPs generation. This impact makes a smother load pattern for whole system and increases system total efficiency.

7.2 Future Research

Based on the thesis outlines the following topics are recommended for further researches:

- Based on the proposed models, modeling of simultaneous participation of MEPs in gas and electricity wholesale markets as strategic energy players.
- Utilizing nodal prices and comprehensive modeling of energy network can enhance the accuracy of results and guarantee its application in real energy system.
- Furthermore, modeling of competition among players of electricity market and modeling a market with multiple strategic players can give a better model for current conditions of energy market.
- In the long term point of view, proper approach can be offered for planning of energy system by changing the resources mix of operation centers, in the proposed model especially considering the competitive constraints of local energy networks.

7.3 List of Publications

Journals Papers

- **M. Y. Damavandi**, Mohsen Parsa Moghaddam Mahmoud-Reza Haghifam Miadreza Shafie-khah João P.S. Catalão "*Modeling operational behavior of plug-in electric vehicles parking lot in multi-energy system*", IEEE Transaction on Smart Grid,Vol. 7, No. 1, pp. 124-135, January 2016.
- M. Shafie-khah, N. Neyestani, **M. Y. Damavandi**, F.A.S. Gil, J.P.S. Catalão, "*Economic and technical aspects of plug-in electric vehicles in electricity markets*", Renewable and Sustainable Energy Reviews (Elsevier), Vol. 53, pp. 1168-1177, January 2016.
- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, G. Chicco, J.P.S. Catalão, "*Stochastic modeling of multi-energy carriers dependencies in smart local networks with distributed energy resources*", IEEE Transactions on Smart Grid, Vol. 6, No. 4, pp. 1748-1762, July 2015.
- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J. Contreras, J.P.S. Catalão, "*Allocation of plug-in vehicles' parking lots in distribution systems considering network-constrained objectives*", IEEE Transactions on Power Systems, Vol. 30, No. 5, pp. 2643-2656, September 2015.

Book Chapters

- **M. Y. Damavandi**, M.P. Moghaddam, M.-R. Haghifam, M. Shafie-khah, J.P.S. Catalão, "*Modeling reserve ancillary service as virtual energy carrier in multi-energy systems*", in: Technological Innovation for Cloud-based Engineering Systems, Eds. L.M. Camarinha-Matos, T.A. Baldissera, G. Di Orio, F. Marques, DoCEIS 2015, IFIP AICT 450,SPRINGER, Heidelberg, Germany, pp. 431-439, April 2015.
- **M. Y. Damavandi**, M.P. Moghaddam, M.-R. Haghifam, M. Shafie-Khah, J.P.S. Catalão, "*Stochastic modeling of plug-in electric vehicles' parking lot in smart multi-energy system*", in: Technological Innovation for Collective

Awareness Systems, Eds. L.M. Camarinha-Matos, N.S. Barrento, R. Mendonca, DoCEIS 2014, IFIP AICT 423,SPRINGER, Heidelberg, Germany, pp. 332-342, April 2014.

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-Khah, J.P.S. Catalão, "*Modeling energy demand dependency in smart multi-energy systems*", in: Technological Innovation for Collective Awareness Systems, Eds. L.M. Camarinha-Matos, N.S. Barrento, R. Mendonça, DoCEIS 2014, IFIP AICT 423, SPRINGER, Heidelberg, Germany, pp. 259-268, April 2014.
- E. Heydarian-Forushani, M. Shafie-Khah, **M. Y. Damavandi**, J.P.S. Catalão, "*Optimal participation of DR aggregators in day-ahead energy and demand response exchange markets*", in: Technological Innovation for Collective Awareness Systems, Eds. L.M. Camarinha-Matos, N.S. Barrento, R. Mendonça, DoCEIS 2014, IFIP AICT 423, SPRINGER, Heidelberg, Germany, pp. 353-360, April 2014.

Conference Papers

- **M. Y. Damavandi**, M.P. Moghaddam, M.-R. Haghifam, M. Shafie-khah, J.P.S. Catalão, "*Modeling operational behavior of plug-in electric vehicles' parking lot in multi-energy systems*", in: Proceedings of the 2016 IEEE PES Transmission Distribution Conference Exposition — TD 2016, Dallas, Texas, USA, 2-5 May, 2016 (accepted).
- N. Neyestani, **M. Y. Damavandi**, T.D.P. Mendes, J.P.S. Catalão, G. Chicco, "*Effect of plug-in electric vehicles traffic behavior on multi-energy demand's dependency*", in: Proceedings of the IEEE EnergyCon 2016 Conference, Leuven, Belgium, April 4-8, 2016 (accepted).
- M. Shafie-khah, M.H. Shoreh, P. Siano, N. Neyestani, **M. Y. Damavandi**, J.P.S. Catalão, "*Oligopolistic behavior of wind power producer in electricity markets including demand response resources*", in: Proceedings of the 2016 IEEE Power Energy Society General Meeting — PESGM 2016, Boston, Massachusetts, USA, July 17-21, 2016 (accepted).

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, G. Chicco, J.P.S. Catalão, "*Stochastic modeling of multienergy carriers dependencies in smart local networks with distributed energy resources*", in: Proceedings of the 2016 IEEE PES Transmission Distribution Conference Exposition — TD 2016, Dallas, Texas, USA, 2-5 May, 2016 (accepted).

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J. Contreras, J.P.S. Catalão, "*Allocation of plug-in vehicles' parking lots in distribution systems considering network-constrained objectives*", in: Proceedings of the 2016 IEEE PES Transmission Distribution Conference Exposition — TD 2016, Dallas, Texas, USA, 2-5 May, 2016 (accepted).

- **M. Y. Damavandi**, S. Bahramara, M.P. Moghaddam, M.-R. Haghifam, M. Shafie-khah, J.P.S. Catalão, "*Bi-level approach for modeling multi-energy players' behavior in a multi-energy system*", in: Proceedings of the IEEE Power Tech 2015 Conference, Eindhoven, Netherlands, 29 June - 2 July, 2015.

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, J. Contreras, "*PEV parking lot behavior equilibria in energy and reserve markets*", in: Proceedings of the IEEE Power & Energy Society General Meeting, PESGM 2015, Denver, Colorado, USA, July 26-30, 2015.

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, "*Modeling the PEV traffic pattern in an urban environment with parking lots and charging stations*", in: Proceedings of the IEEE Power Tech 2015 Conference, Eindhoven, Netherlands, 29 June - 2 July, 2015.

- N. Neyestani, **M. Y. Damavandi**, J.P.S. Catalão, "Assessment of PEV owners' preferences impact on PEV parking lot transactions", in: Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC 2015 (technically co-sponsored by IEEE), Wollongong, Australia, USB flash drive, 27-30 September, 2015.

- N. Neyestani, **M. Y. Damavandi**, J.P.S. Catalão, "*Analyzing the effect of various PEV owner's charging tariffs on PEV PL's market equilibrium*", in: Proceedings of the IEEE Region 8 International Conference on Computer as a

Tool — EUROCON 2015, Salamanca, Spain, USB flash drive, 8-11 September, 2015.

- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, G. Chicco, "*Uncertainty characterization of carrier-based demand response in smart multi-energy systems*", in: Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives — PowerEng 2015 (technically co-sponsored by IEEE), Riga, Latvia, USB flash drive, May 11-13, 2015.
- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, J. Contreras, "*Modeling the optimal behavior of PEV parking lots in energy and reserve market*", in: Proceedings of the 5th IEEE PES Innovative Smart Grid Technologies Europe Conference — ISGT Europe 2014, Istanbul, Turkey, October 12-15, 2014.
- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, G. Chicco, "*Modeling the carrier dependencies on demand-side in a smart multi-energy local network*", in: Proceedings of the 2014 Smart Grid Conference — SGC'14 (technically co-sponsored by IEEE), Tehran, Iran, CD-R, December 9-10, 2014.
- N. Neyestani, **M. Y. Damavandi**, M. Shafie-khah, J.P.S. Catalão, "*Comparison of various operational statuses of PIEV aggregators with home-charged EVs and parking lots*", in: Proceedings of the 2014 IEEE Power Energy Society General Meeting — PESGM 2014, Washington, DC Metro Area, USA, USB flash drive, 27-31 July, 2014.

Submitted Journal Papers

- **M. Y. Damavandi**, N. Neyestani, M. Shafie-khah, J.P.S. Catalão, "*Aggregation of Demand Side Resources under the Concept of Multi-Energy Players as a Flexible Source in the Market Environment*", Submitted to IEEE Transactions on Smart Grid.
- N. Neyestani, **M. Y. Damavandi**, A. G. Bakirtzis, J.P.S. Catalão, "*PEV Parking Lot Equilibria with Energy and Reserve Markets Considering the PEV Owner Preferences — Part I: Model and Formulation*", Submitted to IEEE Transactions on Power Systems.

- N. Neyestani, **M. Y. Damavandi**, A. G. Bakirtzis, J.P.S. Catalão, "*PEV Parking Lot Equilibria with Energy and Reserve Markets Considering the PEV Owner Preferences — Part II: Numerical Results*", Submitted to IEEE Transactions on Power Systems.

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