

# Integrating Renewable Energy in Smart Grid System: Architecture, Virtualization and Analysis

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## Abstract

Renewable energy sources (RESs) and energy storage systems (ESSs) are the key technologies for smart grid applications and provide great opportunities to de-carbonize urban areas, regulate frequency, voltage deviations, and respond to severe time when the load exceeds the generation. Nevertheless, uncertainty and inherent intermittence of renewable power generation units impose severe stresses on power systems. Energy storage systems such as battery energy storage system enables the power grid to improve acceptability of intermittent renewable energy generation. To do so, a successful coordination between renewable power generation units, ESSs and the grid is required. Nonetheless, with the existing grid architecture, achieving the aforementioned targets is intangible. In this regard, coupling renewable energy systems with different generation characteristics and equipping the power systems with the battery storage systems require a smooth transition from the conventional power system to the smart grid. Indeed, this coordination requires not only robust but also innovative controls and models to promote the implementation of the next-generation grid architecture. In this context, the present research proposes a smart grid architecture depicting a smart grid consisting of the main grid and multiple embedded micro-grids. Moreover, a focus has been given to micro-grid systems by proposing a “Micro-grid Key Elements Model” (MKEM). The proposed model and architecture are tested and validated by virtualization. The implementation of the virtualized system integrates solar power generation units, battery energy storage systems with the proposed grid architecture. The virtualization of the proposed grid architecture addresses issues related to Photovoltaic (PV) penetration, back-feeding, and irregularity of supply. The simulation results show the effect of Renewable Energy (RE) integration into the grid and highlight the role of batteries that maintain the stability of the system.

**Keywords:** Smart Grid; Micro-grid; Virtualization; Storage Energy; Renewable Sources.

## Acronyms

RESs	Renewable energy sources	HAN	Home Area Network
RE	Renewable energy	BAN	Building Area Network
ESSs	Energy Storage Systems	IAN	Industrial Area Network
MKEM	Micro-grid Key Elements Model	SDs	Smart Devices
PV	Photovoltaic	SP	Service Provider
RE	Renewable Energy	HVAC	Heating Ventilating and Air Conditioning
ICT	Information and Communication Technology	PEVs	Plug in Electric Vehicles
NIST	National Institute of Standards and Technology	SM	Smart Meter
SGCN	Smart Grid Communication Network	TOU	Time of Use
SGAM	Smart Grid Architecture Model	RTP	Real Time Pricing
SGCG	Smart Grid Coordination Group	SSM	Supply Side Management
CSIRO	Commonwealth Scientific and Industrial Organization	DC	Direct Current
DG	Distribution Generations	AC	Alternating Current
UCC	Universal Charge Controller	IC	Incremental Conductance
MAS	Multiagent System	SSM	Supply Side Management
EMS	Energy Management System	SoC	State of Charge
ESSs	Energy Storage Systems	BESS	Battery Energy Storage Systems
SOS	System of Systems	TMY	Typical Meteorological Year
MG	Micro-grid	SG	Smart Grid
LC	Local Controller	GHG	Greenhouse gas

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## 1. Introduction

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Notwithstanding the Paris Agreement, a technological transient from hydrocarbon-based power generating units to the post-petroleum-based sources, there is intangible projective evidence of such transition in the world [1]. For instance, recent studies into the projective period indicate that energy consumption will increase from 663 to 736 quadrillion Btu between 2015 and 2040 [2], with an expected increase in carbon dioxide annual emissions from 31.2 to 45.5 billion metric tons. Moreover, recent investigations demonstrate that the possibility of the energy paradigm shift to sustainable low carbon economy at European Union, although, has come into conflict between the Northern, Western Member states against Central and Eastern European, causing an obstruction of swiftly advancing de-carbonization [1]. To clarify the importance of integrated renewable energy sources, European Union set a goal of reaching 27%

41 in gross final energy consumption from renewable energy sources by the end of 2030 [3].  
42 Therefore, coupling of renewable energy sources (RESs) and electric grid has gained  
43 momentum and is being widely accepted as an alternative power supply. In Germany,  
44 expansion of renewable energies is a central pillar of the energy transition towards a non-  
45 nuclear renewable system [4]. In addition, the global installed capacity of solar photovoltaic  
46 (PV) has dramatically increased as part of a shift from fossil fuel-based power generations  
47 towards reliable, clean, efficient and sustainable fuels [5]. The goal is to maintain grid stability  
48 with high penetration of RESs while satisfying consumer demand. In this regard, it is expected  
49 that this integration could reduce carbon dioxide emissions and other air pollutants. As  
50 mentioned before, by successful coordination between RESs and power systems, ESSs could  
51 improve the reliability, security, and resiliency of micro-grid applications by offering ancillary  
52 services such as peak shaving.

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### 54 **1.1. Literature review**

55

56 The need for integration of RESs into the power system is to provide a wide variety of  
57 socioeconomic and environmental benefits, and to minimize the GHG emissions from  
58 conventional power plants [6]. Andújar et al. [7] explained two main reasons for justifying the  
59 transit towards coupling renewable energy sources with power plant-based fossil fuels. These  
60 reasons are [7]: environmental concerns, and power losses. However, the stochastic and the  
61 intermittent behavior of the PV power generations pose severe stresses to the grid lead to the  
62 instability in the electricity supply [8]. More precisely, the intermittent energy sources can fail  
63 to guarantee the continuity and reliability of the power supply [9]. Besides of the  
64 aforementioned challenges of PV integration, the back-feeding imposes tremendous operational  
65 challenges in power systems [10]. When the local PV generation exceeds the local load demand,  
66 reverse power flows occurs. The reverse power induces a voltage rise within distribution  
67 networks [10]. Along with that, Calpa et al. [11] analyzed the effects of high PV penetration as  
68 the main energy source for the Spanish electrical grid. The authors highlighted the effect of  
69 high PV penetration which can lead to a reduction on the local consumption or even negative  
70 consumption. The results showed that the electrical grid should be able to respond to this new  
71 shape by adapting the power generations, controlling consumption or using storage systems  
72 [11]. Similarly, Cohen et al. [12] simulated a use case of Sacramento feeders and showed  
73 negative values for load demand and a largest reverse power flow. It was shown that feeder  
74 location (i.e. climate) has a stronger impact than feeder type on the incidence of the reverse

75 power flow and reductions in peak loading [12]. Moreover, Nguyen and Kleissl [13]  
76 highlighted the impact of PV power generation units, can be reverse power flow, high voltage  
77 level and increasing number of tap operations. To deal with the reverse power flow,  
78 decentralized PV power generation units have been proposed instead of the centralized  
79 generation units [13]. Besides that, integration of renewable power generation units as new  
80 distributed generations encompassing large scale at the transmission level, medium scale at the  
81 distribution level and small scale on commercial or residential building can present challenges  
82 for the dispatch ability and control ability of these resources and for operation of the electricity  
83 system [14].

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85 In this context, the traditional grid must be improved to cope with the increased penetration  
86 of PV and its inherent intermittency. In this framework, energy storage systems can play a  
87 significant role in meeting or mitigating the mentioned challenges and dealing with the  
88 variations of PV power output. From technical expertise point of view, the energy storage  
89 technology is considered as a one of the disruptive technologies that could change the way the  
90 energy supply, for end-users [15]. For instance, by installing a storage battery as an energy  
91 buffer, system stability can be improved [15]. In this sense, the generated PV power can be  
92 stored, or fed into the micro-grid. Therefore, in order to accommodate uncertainty of future  
93 realizations of demand and generation, sizing energy storage systems plays a prominent role in  
94 the micro-grid [16]. This can mitigate the intermittent and fluctuations of PV power generation  
95 units. In addition, the integration of energy storage systems during peak load periods can be  
96 also useful to shift electrical demands from on-peak to off-peak [17], [18]. In this regard, it is  
97 becoming critical to integrate analysis and design of power electronics and power systems in  
98 order to support this integration.

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100 The integration of new technologies into the conventional grid requires both innovative and  
101 robust modeling of various components to incentivize and implement Smart Grid architectures  
102 with RESs. In order to upgrade the current power grid, it is required to go through existing  
103 Smart Grid architectures that could support RESs integration and accommodate higher levels  
104 of variable ESSs. In this context, many researchers have proposed broad definitions of smart  
105 grid. A smart grid can be defined as an upgraded electrical network, relying on bi-directional  
106 communication infrastructure and power exchange between suppliers and consumers, due to  
107 the pervasive incorporation of intelligent communication monitoring and management systems  
108 [19]. It is the coexistence of power flow, Information and Communication Technology (ICT)

109 and financial transactions. In this way, the ICT in the smart grid can make the existing  
110 infrastructure including generation, transmission, distribution, and consumers more efficient  
111 and yet can guarantee the successful coordination between local distributed renewable  
112 generation units and power system [20]. Thus, the smart grid is an evolution of the power grid,  
113 based on the integration of new technologies, smart devices, advanced communications and  
114 controls. In this regard, many researchers have proposed a design of Smart Grid architecture to  
115 support integration of RESs. In Ref. [21], a generic hierarchical architecture as a framework of  
116 various energy management systems has been proposed to deal with the challenges of the  
117 increase in penetration of the distributed renewable energy generation. Furthermore, the U.S.  
118 Energy Independence and Security Act directed the National Institute of Standards and  
119 Technology (NIST) to propose a NIST model defining the Smart Grid as a coexistence of seven  
120 domains in 2007 [18]. Whereas the NIST conceptual model provides a wide picture of how the  
121 fundamental components of the smart grid connect and communicate and seems to be a  
122 promising reference architecture for standardization of interfaces, it still presents some  
123 drawbacks related to the lack of definition of Micro-grid systems with owners of energy  
124 sources. Hence, the Smart Grid Coordination Group (SGCG), driven by the European  
125 Committee for Standardization (CEN), European Committee for Electrotechnical  
126 Standardization (CENELEC) and European Telecommunications Standardization Institute  
127 (ETSI) designed the Smart Grid Architecture Model (SGAM) and thus by international experts  
128 [22]. The SGAM as a three-dimensional framework consisting of domains, zones, and layers,  
129 provides a structural approach for modeling smart grid use cases [23]. In this sense, the NIST  
130 model has been extended by the European Community which integrates a “Distributed Energy  
131 Resources” (DERs) domain. The updated model reflects the growing importance of DER,  
132 which includes non-traditional sources such as customer-owned solar and wind power systems.  
133 These DERs with advanced functionalities enable power system designers to incorporate  
134 “Micro-grids” into the existing grid architectures.

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136 In this way, during the next decade, micro-grids will emerge as an alternative to the current  
137 centralized energy generation systems, because they can provide economic benefits through  
138 avoiding long distance transmission [24]. Also, they can enhance the integration of small and  
139 medium size of DER units into the electric grid [24]. Moreover, the micro-grids enable  
140 effectively the main grid to disconnect different part of that when power is disrupted. Hence  
141 the power system can be more adaptive and reliable against possible either fluctuation or fault.  
142 In this sense, a Micro-grid model is essential for after-the-fact event analysis. It can reduce

143 system complexity and provide better insight into RESs integration studies. Furthermore, as  
144 one of the possible solution to the inherent intermittent renewable power generation units is a  
145 grid coupled with ESSs, Wood et al. [25] have used the “UltraBattery” technology, an entire  
146 new class of advanced lead-acid batteries invented by the “Commonwealth Scientific and  
147 Industrial organization” (CSIRO), to manage variability and shift energy demand. This  
148 technology focused on Micro-grid systems to combine renewable energy sources with a storage  
149 system, thus providing multiple benefits, making renewable resources reliable and dispatchable  
150 [25]. Adonis et al. [26] presented an analysis of control strategies developed for a Micro-grid  
151 control structure, when it is integrated with renewable energy sources. The authors developed  
152 a control strategy for the load management and performed an analysis through  
153 MATLAB/Simulink simulation. The objective was to improve Micro-grid operation stability  
154 under irregularities of the input voltage. Similarly, in Ref. [27], distribution generations (DG)  
155 and renewables with seasonal variation at different locations have been modeled by employing  
156 PSCAD software. The goal was to maintain the power quality of the system when the load has  
157 fluctuation. The authors proposed a generalized approach to design, determine the capacity,  
158 required for the micro-grids with metrics to meet the power quality indexes [27].

159

## 160 **1.2. Motivation, objectives, and innovative contribution**

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162 Generally, a micro-grid is composed of renewable energy generations, energy storage  
163 systems (ESSs), and loads, which can operate in grid-connected and stand-alone modes. The  
164 primary objective of the present article is to depict a smart grid architecture consisting of the  
165 main grid and multiple embedded micro-grids. In this article, “Micro-grid Key Element model”  
166 is employed to model the above architecture that would be double-beneficial: 1) predicting the  
167 effect of energy sources on power system such as solar energy 2) minimizing the cost and risk  
168 of the proposed architecture before implementation. Moreover, a virtualized power system  
169 would open new avenues for revenue generation as well as utilize computing and network  
170 resources more efficiently across the entire power grid. The virtualized grid system would  
171 provide increasing stability of the physical grid and isolate problems more quickly.

172 According to the literature, the proposed architecture in this article enjoys several  
173 advantages, compared to the recent studies [28], [29], [30], [31]. For instance, Sermakani et al.  
174 [28] proposed a multi agent (mesh topology) system based on a decentralized micro-grid  
175 control. However, the maintenance of the proposed topology is very difficult along with its  
176 tough administration. Moreover, the cost of implementation of such architecture is higher than

177 other network topologies, making it an expensive option. In addition, Wang et al. [29] proposed  
178 a three-layer architecture of a smart grid, highlighting the energy trading among MGs by  
179 employing Peer-to-Peer (P2P) networks. Nevertheless, the unstructured networks such as P2P  
180 lead to difficulties with communication resources, and limit the possibility for managing  
181 different plans [32]. To address the above drawbacks, the present article proposes a Smart Grid  
182 as a system of multiple embedded micro-grids, including a double-layer controller. The high-  
183 level of controller is the centralized controller at the main grid, and the low-level of controller,  
184 known as a local controller is associated with the micro-grid level. In addition, Ref. [30]  
185 proposed a transformative architecture for a normal operation and self-healing of networked  
186 micro-grids (MGs), composed of both cyber links for communication and a physical common  
187 bus for power exchange. However, the financial flow has not been considered within this  
188 architecture. Furthermore, Ghiani et al. [31] presented multidisciplinary key interactions in a  
189 Smart Distribution Network (SDN) to the strong connection between the design and operation  
190 of SDN. Therefore, the connections are established between three main fields: management and  
191 control system (MCS), monitoring system (MS), communication and processing system (CPS).  
192 Nevertheless, the market interaction and financial transactions have not been taken into  
193 consideration in terms of necessary multidisciplinary approach to the design of the smart grid  
194 architecture. In this regard, in addition to the above connections, the proposed smart grid  
195 architecture in the present article has a connection with the market interaction and financial  
196 transactions to address the above gaps.

197

198 The main contribution of the present article can be categorized as follows:

199

- 200 1. Presenting the Smart Grid as a System of multiple embedded micro-grids;
- 201 2. Introducing a micro-grid consisting of multiple nano-grids;
- 202 3. Coupling of the proposed grid structure with solar power generation units, and the effect  
203 of their penetration on power system is discussed;
- 204 4. The proposed MKEM is optimally designed and accurately modeled in the power-  
205 systems simulation tool GRIDLAB-D;
- 206 5. Integrating ESSs into the proposed grid structure to maintain system stability.

207

208 To sum up, in the following paragraphs, a smart grid architecture using embedded systems  
209 of micro-grids is presented and proposed through MKEM modeling. The main objective of  
210 introducing such architecture is to reduce system complexity and improve flexibility of the

211 system. The introduced smart micro-grid is composed of renewable energy generations, energy  
212 storage systems (ESSs), and loads, which can operate in grid-connected and stand-alone modes.  
213 Then, the proposed micro-grid model is implemented to test integration and penetration of  
214 RESs.

215 In addition, the rest of the article is organized as follows: the proposed Smart Grid  
216 architecture is presented in Section II. Section III depicts the elements of the proposed  
217 architecture by focusing on micro-grid and presenting a MKEM. Results and discussion are  
218 provided in Section IV. Finally, the outcome of the article is summarized and concluded in  
219 section V.

220

## 221 **2. Proposed smart grid architecture**

222 The backbone of a smart grid, known as a complex System of Systems (SOS) [33], highlights  
223 ESS technology to reach better asset utilization, while maintaining reliable system operation,  
224 demand response, and environmental protection through employing various generation types  
225 (e.g. solar and wind). In this regard, the main concept of the smart grid revolves around bi-  
226 directional communication and power flow according to the definition proposed by the NIST  
227 Smart Grid Conceptual Reference Model, through seven domains which are: bulk generation,  
228 transmission, distribution, markets, operations, service provider, and customer.

229

230 However, Smart Grids have to be analyzed from a SoS point of view to realize their full  
231 potential and optimize the whole system [33]. Arasteh et al. used the concept of SoS to model  
232 the expansion of DGs which may belong to the distribution companies or the private investors,  
233 considering the independent behavior of each system with respect to other entities [34]. As  
234 private investors and distribution companies are autonomous, heterogeneous and independently  
235 operable systems are connected to provide a common goal, their behavior could be analyzed  
236 from a SoS perspective to model their correlation. The SoS perspective aggregates different  
237 autonomous systems, interacting on various levels, which are characterized by operational and  
238 managerial independence [35]. A representative example of this perspective is the energy  
239 management sector in which the Smart Grid is known as a complex system composed of  
240 heterogeneous and independent sub-systems (e.g., consumers, producers, prosumers, storages,  
241 etc.) that interact to compete or cooperate [36]. Different strategies for coordinating constituent  
242 systems of a SoS exist such as centralized coordination, where a Central Controller (CC)  
243 coordinates constituent systems at the SoS level [37]. A decentralized strategy for SoS can also

244 be used, where neither a CC nor a pre-specified rule or agreement for constituent systems exists  
 245 [37]. Another strategy for SoS is a coordinating strategy which is considered as a hybrid strategy  
 246 that mixes both centralized and decentralized coordination.

247  
 248 In this regard, the Smart Grid should be considered as a complex system where the main grid  
 249 contains multiple micro-grids. These micro-grids consist of several nano-grids known as small  
 250 residential power systems with renewable sources, storage systems, and domestic loads. The  
 251 nano-grids and micro-grids are the electric grids which correspond to the residential power  
 252 systems and neighborhoods, respectively. They are also connected to the power distribution  
 253 grid or to another micro-grid [31]. The micro-grid involves different technologies and contains  
 254 loads, distributed generators (PV or wind turbines), Distributed Systems, Electric Vehicles  
 255 (EVs), ESSs and power electronic systems [32], [33]. In this regard, power electronic systems  
 256 are required to enable the micro-grid to operate in grid-connected or island modes. Moreover,  
 257 these systems are needed to connect DER to the nano-grids using inverters for PV or batteries  
 258 to obtain the required frequency.

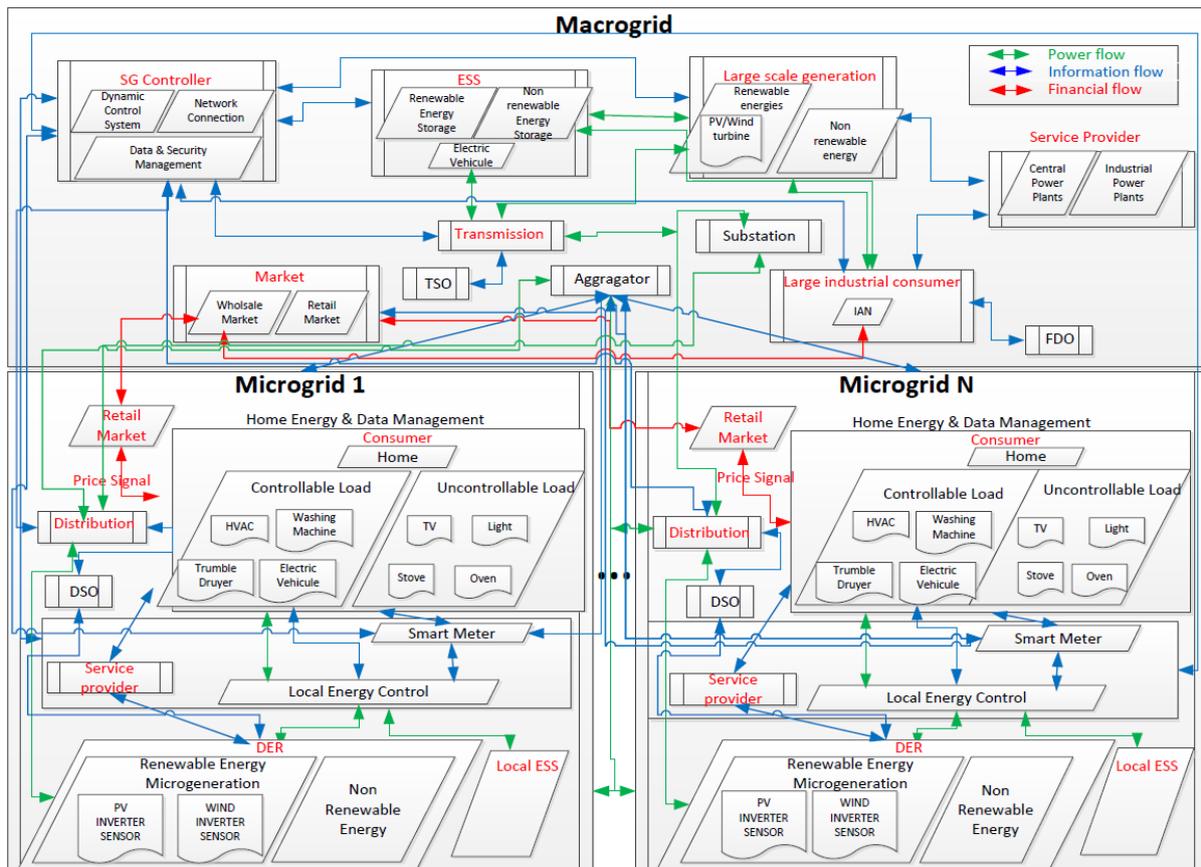


Fig.1 The proposed Smart Grid Architecture.

260  
 262 To deal effectively with the challenges of integrating RESs and nano/micro-grids with the  
 263 electric grid, contemplating electric source intermittency and load inconsistency, this study

264 proposes a smart grid architecture, depicted in Fig. 1. The proposed architecture consists of a  
265 double-layer controller, one of which is a centralized controller at the main grid level and the  
266 other one is a local controller (LC) that controls the micro-grid level. In centralized operation,  
267 each LC receives the set points of the corresponding Smart Grid (SG) Controller. However, this  
268 type of control has low reliability and redundancy [38]. In decentralized operation, each local  
269 controller decides locally [39]. In the present research, the proposed architecture uses a hybrid  
270 approach defining both the centralized and decentralized operations within the main grid.  
271 Moreover, three flows can be distinguished: the power flow which can be bidirectional in case  
272 of batteries or consumers with production capabilities, the information flow which consists of  
273 an ICT platform, and the financial flow related to the commercial transactions including  
274 retailing and wholesaling [18]. The proposed SoS architecture encompasses three levels which  
275 are: the macro-grid level referring to the main grid, the micro-grid level and the nano-grid level.  
276 The macro-grid level contains the transmission system with large scale generation systems, ESS  
277 to store different kind of electricity such as an electrochemical or mechanical energy system,  
278 and large industrial consumers. Moreover, a Transmission System Operator (TSO) is used to  
279 transfer energy in different forms such as natural gas or the electrical power, and a service  
280 provider is used to interact with the operators and ensure proper functioning of the smart grid.  
281 At the micro-grid level, two objectives can be distinguished considering micro-grid operation  
282 modes. In grid-connected mode, financial transactions are made using interactions with the  
283 wholesale markets. However, in islanded mode, the energy and economic flows of the micro-  
284 grid are managed using a local market named retail market, and energy efficiency services are  
285 provided. In both modes, the micro-grid guarantees in real time the stability and the security of  
286 the network. At the nano-grid level, peak-shaving, load leveling, and load-shifting are  
287 performed to reduce energy losses and energy cost employing end user's preferences, price  
288 signals, management of local generation and local ESS. Moreover, the demand response can be  
289 achieved through dynamic pricing to reduce the gap between supply and generation. The smart  
290 meter is used for reading and transmitting measurements of the power consumption, generation,  
291 and voltage [40]. It also interacts with a two-way communication with retailers and controllers.  
292 Moreover, it handles various bill models such as Time of Use (TOU) or Real Time Pricing  
293 (RTP).

294  
295  
296

### 297 **3. The proposed micro-grid model**

299 The micro-grid is a distribution system with local DERs which is connected to the traditional  
 300 centralized electrical grid but is able to operate autonomously [41]. A micro-grid could be a  
 301 kind of smart grid equipped with advanced computer communication technologies and smart  
 302 meters providing more flexibility and reliability for control and protection of the system [41].  
 303 Today, the micro-grids include different types of renewable sources to achieve environmental  
 304 and economic benefits [42]. In this sense, the micro-grid has emerged as a flexible architecture  
 305 for deploying distributed energy resources (DERs) that can meet wide-range of needs for  
 306 different communities [43]. Especially, PV system is one of the most effective DERs in micro-  
 307 grids [41]. Moreover, the micro-grids enhance market operations and consumer participation  
 308 [44]. In this regard, the micro-grid energy markets allow small-scale participants such as  
 309 consumers to actively trade energy within their community in real time [44]. Therefore, they  
 310 facilitate a sustainable, reliable, and local balance of generation and consumption [44]. In this  
 311 context, Eq. (1) identifies the relationship between the generated power and the load power  
 312 within a micro-grid at each time interval:

313

$$314 \quad \sum P_{loads} = P_{pv} + P_{ESS} + P_{market} \quad (1)$$

315

316 where  $P_{loads}$ ,  $P_{pv}$ ,  $P_{ESS}$ , and  $P_{market}$  are the load, the power generated by the PV system, the  
 317 power provided by ESS, and the purchased and sold power from/to Micro-grid, respectively.  
 318 To gather the requirements of a system including internal and external influences and highlight  
 319 the role of RESs and ESSs, use cases and standards are considered as an efficient method to  
 320 determine requirements and to address interoperability issues. In this regard, Unified Modeling  
 321 Language (UML) is recommended to allow the use within further model-based development  
 322 efforts and to ease the customization by implementers in their own tool chain [23]. For instance,  
 323 Eger et al. identified essential use-cases of a microgrid scenario by employing UML diagrams  
 324 [45]. Further, the actors involved in the use-cases were divided into “people & organization”  
 325 such as prosumer, service provider, consumer, retailer, and “systems & devices”. Similarly,  
 326 Gopalakrishnan et al. analyzed micro-grid operational scenarios using UML and defined  
 327 business use-cases, and technical use-cases referring to control and management use-cases [46].  
 328 Business use-cases involve selling and buying energy to/from external markets, selling  
 329 balancing and ancillary services, providing islanding mode, and offering communication  
 330 platform for energy trading. However, the technical and management use cases include  
 331 balancing supply and demand on the varied time scales, auto configuration, monitoring and

332 state analyses, forecasting generation and consumption, and optimizing power flow to reduce  
 333 losses. Furthermore, Sultan et al. focused on two components of smart power system that are  
 334 transformers and smart meters and presented system requirements through UML use-case  
 335 diagrams that are used to describe actions and functionalities of the system [47]. Moreover, in  
 336 Ref. [48], the authors focused on modeling smart grid functional requirements using use-case  
 337 descriptors and UML class diagrams to easily track disturbances and outage events that can  
 338 happen in the electric grid environment. In this regard, the main purpose of using model driven  
 339 methodology and high level or summary use-case diagrams is to clearly describe the functional  
 340 requirement of a system, help manage complexity and pave a way for building smart grid  
 341 applications [49],[50]. In this context, a “Micro-grid Key Elements Model” (MKEM) as high-  
 342 level use-case diagram combining business and control and management aspects is proposed.

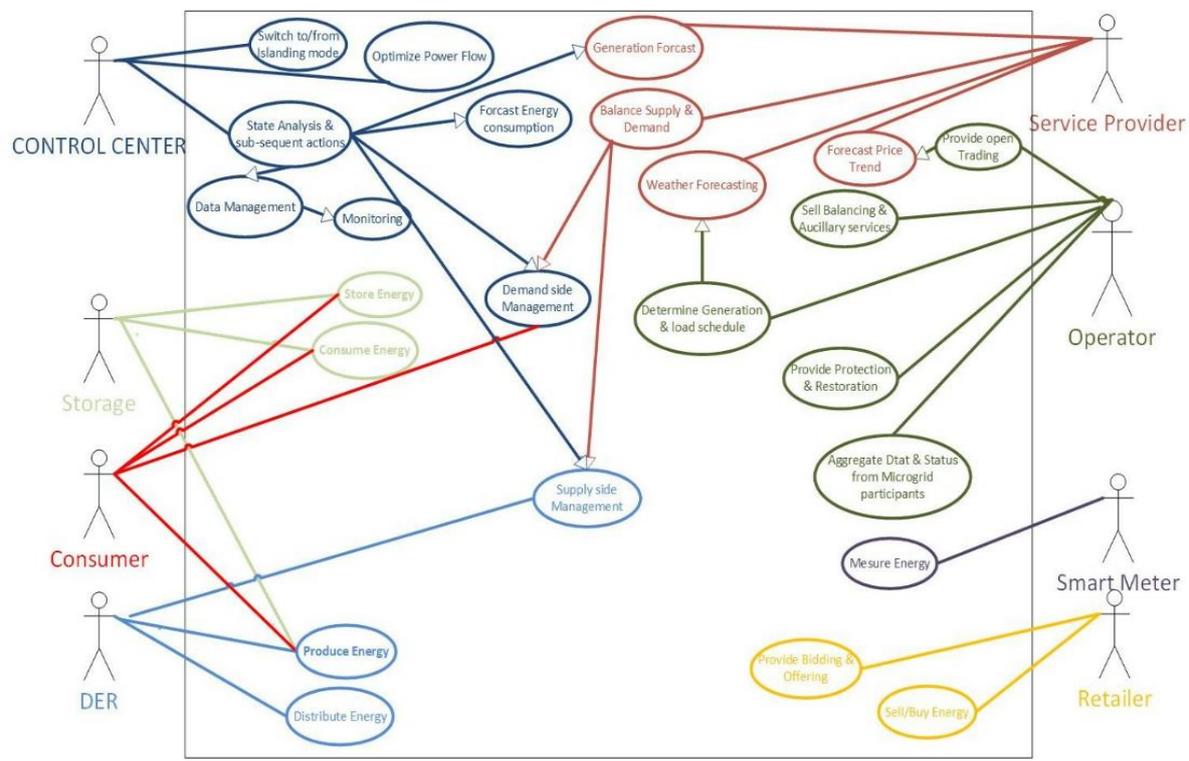


Fig. 2 Proposed MKEM Model.

347 The Fig. 2 shows the interactions of actors, the functionalities captured and the relationships  
 348 among actors within business, control and management levels. The proposed MKEM consists  
 349 of eight actors which are defined as follows:

350  
 351 1) Consumer

352 The end-user or consumer can be classified into three groups: a residential customer, a  
 353 commercial customer, and an industrial customer. Therefore, three networks can be defined as

354 follows: Home Area Network (HAN), Building Area Network (BAN) and Industrial Area  
355 Network (IAN). The HAN consists of the following entities: Smart Devices (SDs), a Home  
356 Gateway (HG) and a Service Provider (SP) [51]. It is a network connecting devices able to send  
357 and receive signals from other devices and applications. The HAN is thus an enabling factor  
358 for the evolution of the smart home and other applications, such as home energy management  
359 (HEM) systems [52]. In addition, BAN and IAN are used for commercial and industrial  
360 customers with focus on building automation, heating ventilating and air conditioning (HVAC)  
361 and other industrial energy management applications [53]. In this regard, the consumer within  
362 a micro-grid can have a controllable load such as HVAC, washing machine, water heater,  
363 electric vehicle, and an uncontrollable load such as TV, lights, stove, and oven. These smart  
364 appliances provide the consumers with information on incentives and disincentives, offering  
365 choices and motivations, to change their consumption profiles. The objective is to help  
366 balancing supply and demand and to ensure reliability with dynamic pricing and demand  
367 response services considering consumer preferences. This can be achieved by employing  
368 billing, bidirectional flows of energy, information and financial transactions.

369 In this regard, the consumer can perform the following functionalities:

- 370 • Use electricity, generate electricity, store electricity;
- 371 • Engage in DSM to consume less energy during high-consumption hours (peak hours)  
372 or shift its consumption (to off-peak periods).

373

## 374 2) Smart Meter

375 A smart meter is an electronic device that measures energy consumption and exchanges the  
376 information with the electricity supplier for monitoring and billing. This component can  
377 provide the required measurements for various control strategies [18]. By such devices,  
378 consumers can communicate with power generation units and pave a way for controlling the  
379 load.

380 The Smart Meter can perform the following functionalities:

- 381 • Measure energy flow;
- 382 • Exchange information with the electricity supplier.

383

## 384 3) DER

385 DER generally include the distributed generation, and storage systems. These components  
386 can provide benefits such as reducing power losses in transmission system, maintaining grid

387 stability, and improving resiliency. DERs are essential components for the micro-grid whose  
 388 role is to integrate RESs into the power system and to keep the balance between energy demand  
 389 and supply. Moreover, DERs can improve grid reliability, to better manage energy consumption  
 390 and to achieve energy efficiency guidelines. However, the main disadvantage of using DERs is  
 391 their intermittent nature. Therefore, modern electric grids have to support the integration of the  
 392 conventional generation technologies, renewable energy resources, energy storage devices and  
 393 dynamic loads [54]. This interconnection highlights the concept of micro-grid and mitigates the  
 394 issues related to the intermittent behavior of RESs. To enhance the independency aspect, ESSs  
 395 are disconnected from DER and presented as independent components in the proposed model.

396 DER can perform the following functionalities:

- 397 • Distribute and produce energy;
- 398 • Perform Supply Side Management (SSM) with ESSs.

399 In this paper, the generated power  $P_{pv}$  by PV component can be calculated via using solar  
 400 irradiance and PV temperature as showed in Eq. (2):

$$401 \quad P_{pv} = P_n \times (R \div R_{ref}) \times [1 + K_t \times (T_c - T_{ref})] \quad (2)$$

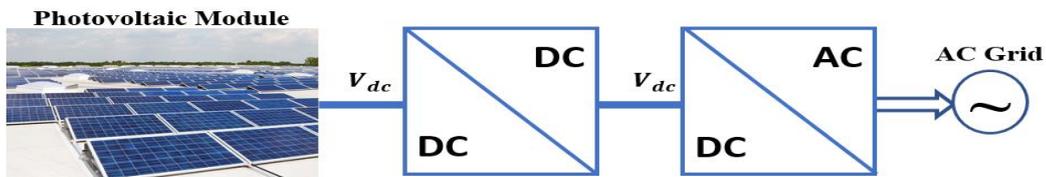
402  
 403 where  $P_n$  is nominal power of PV system at reference conditions,  $R$  is solar irradiance,  $R_{ref}$  is  
 404 solar irradiance at reference conditions,  $K_t$  is temperature coefficient of PV systems,  $T_c$  is  
 405 temperature of PV system °C,  $T_{ref}$  is temperature of PV system at reference conditions, which  
 406 is set to 25°C.

$$407 \quad T_c = T_{amb} + (0.0256 \times R) \text{ and } T_{amb} \text{ is the ambient temperature.}$$

408  
 409 To maintain the stability of the system, the power output of PV system must follow some  
 410 regulations to be within appropriate limits as indicated in Eq. (3):

$$411 \quad P_{pv} \min(t) \leq P_{pv}(t) \leq P_{pv} \max(t) \quad (3)$$

412  
 413 Moreover, the PV system is connected to the grid via an inverter employed to convert Direct  
 414 Current (DC) to Alternating Current (AC). The topology used in this article is depicted in Fig.3:



416  
 417 Fig. 3 PV system topology.  
 418

#### 419 4) Retailer

420 The Retailer is used to sell energy to small lots. Indeed, energy can be bought at the  
421 Wholesale Market and sold to consumers at the Retail Market using bi-directional transactions.  
422 The retail market provides various services to consumers such as creating a small market for  
423 trading energy using bidding and auction for energy sale. Therefore, electricity consumers can  
424 easily switch between different retail electricity providers. This encourages consumers to  
425 provide load reductions using convenient prices.

426 The retailer can perform the following functionalities:

- 427 • Sell and buy energy;
- 428 • Provide bidding and offering.

429

#### 430 5) Local Controller

431 The LC interacts with SG Controller when the micro-grid is connected to the main grid.  
432 Moreover, DER, storage, and controllable loads have a LC, and a two-way communication is  
433 established with the SG Controller. Especially, at the consumer premises, the LC has  
434 bidirectional communications with the Smart Meter (SM) [40]. The controller is connected to  
435 the smart meters installed in a home and connected to home appliances in order to reduce energy  
436 use and aggregate loads via the Advanced Metering Infrastructure (AMI) networks [53]. In this  
437 regard, the SM acting as a gateway is able to aggregate information related to power  
438 consumption and generation [40]. Therefore, the LC can also gather this information and then  
439 send it to the SG Controller. In addition, the LC is responsible for managing the decision of  
440 energy consumption based on local information and the operator prospects.

441 One of the main advantages of employing LC is to provide flexibility with the main grid in  
442 terms of successful interconnection between RESs and the power system. Moreover, when an  
443 outage occurs, the micro-grid should disconnect from the main utility and maintain the normal  
444 operating condition. In this sense, the Local Controller can perform the following  
445 functionalities:

- 446 • Switch to/from islanding mode;
- 447 • Optimize power flow through implementation of optimization algorithms, and  
448 optimize Battery to Grid (B2G) and Grid to Battery (G2B) operations;
- 449 • State analysis and subsequent actions such as: DSM and Supply Side Management  
450 (SSM) to balance supply and demand, forecast both energy generation, and  
451 consumption, and Data management to perform monitoring.

452

## 453 6) Operator

454 The main strategic goal of operators is to achieve operational excellence by reducing costs  
455 involving operation, maintenance and planning of the electric power transmission and  
456 distribution networks [55]. Moreover, the operators are able to be operated effectively when  
457 both consumers and generation units interact with each other.

458 The operators can perform the following functionalities:

- 459 • Sell balancing and auxiliary services;
- 460 • Provide open trading through the forecasted price by the service provider and bidding  
461 offered by Retailers;
- 462 • Determine generation and load schedule through data collected by smart meters and  
463 forecast of weather and generation performed by the micro-grid service provider;
- 464 • Aggregate data and status from micro-grid participants;
- 465 • Provide protection and restoration.

466

467 These functionalities are performed by means of smart meters which collect the required data  
468 such as the output of generation, the load behavior, the weather condition, the voltage data and  
469 the market prices. Moreover, demand response informs the consumer about its energy usage,  
470 allows financial transaction between the consumer and the retailer and provides information  
471 about the prices (low or high) which could be useful to determine the behavior of the battery,  
472 whether to charge or discharge.

473

## 474 7) Service Provider

475 The Service Provider affords different kinds of services to the operators to support them in  
476 the operation of the main grid. In this regard, the Service Provider executes services to  
477 customers and utilities. The operators need to interact with various service suppliers for  
478 ensuring proper functionality of the smart grid. In this context, the service supplier is a key  
479 player in the power market in the framework of smart grids. Moreover, it takes part in the energy  
480 market analysis and coordinates with the consumer. The service provider can charge customers  
481 with time-varying prices such as TOU and RTP. Furthermore, it contributes to other services  
482 such as weather forecasts.

483 The Service Provider can perform the following functionalities:

- 484 • Forecast Generation and weather;

- 485 • Forecast Price trend;
- 486 • Balance Supply and Demand;

487

#### 488 8) Local ESS

489 Local ESS is a local provider of storage capacity for storing and delivering energy. It is  
 490 needed to cover periods of time when the sun is down, and the wind is not blowing [56]. Local  
 491 Storage units ensure the balancing of volatile supply and demand. Pumped Hydro Storage,  
 492 Compressed Air Energy Storage, Batteries, Supercapacitors and Electric Vehicles can be  
 493 classified under ESS. In this regard, Local ESS and energy management units are important to  
 494 avoid wasting the harvested RESs and to enhance its utilization.

495 The Local Storage can perform the following functionalities:

- 496 • Store Energy;
- 497 • Produce and consume energy;
- 498 • Manage Energy to balance supply and demand;

499

500 In fact, the ESS can provide power until it reaches a low state of charge (SoC) then the main  
 501 energy source turns on to charge the ESS [57]. The means of storing that will be used in this  
 502 work is Battery Energy Storage Systems (BESS).

503 Fig. 4 shows the battery model. All elements in this model depend on the battery state of  
 504 charge (SoC) and the temperature (T). The battery system contains a package with  $N_{BS}$  cells  
 505 that are connected in series and  $N_{BP}$  that are connected in parallel.

506 The parameters of the Li-ion battery are defined via look-up tables based on experimental  
 507 data. The terminal voltage of the battery pack  $V_B$  can be calculated as follows [58]:

$$V_B = N_{BS} (V_{OC} - R_o I_B - R_p I_p) \quad (4)$$

$$SoC_B = SoC_B(0) + \frac{1}{3600} \int \frac{I_B}{C_B} dt \quad (5)$$

508 where:

509

$$\frac{dI_p}{dt} = \frac{(I_L - I_p)}{R_p * C_p} = \frac{(I_L - I_p)}{\tau_p} \quad (6)$$

510  $R_o$  is internal resistance,  $C_p$  is polarization capacitance,  $R_p$  is polarization resistance,  $V_{OC}$  is  
 511 open circuit voltage, and  $SoC$  is battery state of charge.

512

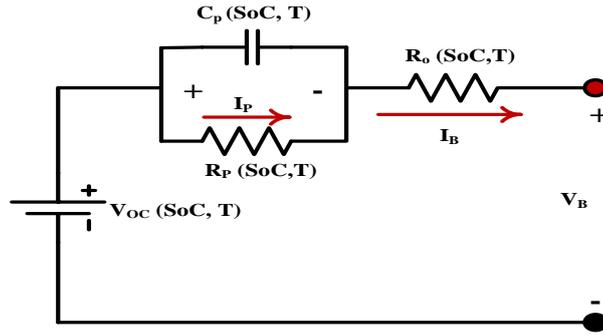


Fig.4 Battery model.

513  
514  
515

516 In this context, an inverter is used to convert DC from batteries to AC. The input variables  
517 of the inverter is the substation voltage  $V_{SUB}$ , the substation current  $I_{SUB}$ , and the transformer  
518 Root Mean Square (RMS) line to line voltage  $V_{LL}$  [59]. In addition, the inverter current will be  
519 a reference current set by the power flow controller depending on the substation voltage. The  
520 inverter model is shown in Fig. 5:

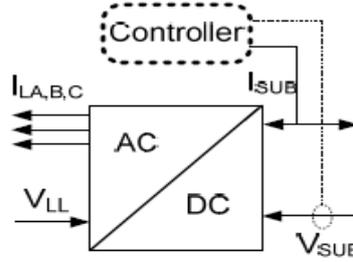


Fig.5. Block diagram of inverter model.

521  
522  
523

524 Furthermore, BESS are connected to the network through a power converter, to receive the  
525 energy of the system. Then this energy will be stored in the battery. In this case, the batteries  
526 are not recharged externally. The subsystem is shown in Fig. 6 [60]. The outputs of the block  
527 are the battery voltage and, the state of charge.

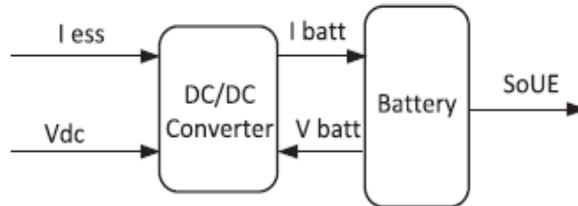


Fig.6. Battery based ESS model [60].

528  
529  
530

531 Besides that, BESS are characterized by a capacity  $C$ , and the state of charge (SoC) of BESS  
532 is defined using Eq. (5). Moreover, the charging or discharging power of BESS and the amount  
533 of stored energy must follow limitations to avoid any damage and to maximize the lifetime of  
534 BESS. Eq. (7) and Eq. (8) illustrate these limits:

$$P_{ESS \min}(t) \leq P_{ESS}(t) \leq P_{ESS \max}(t) \quad (7)$$

$$SOC_{\min} \leq SOC \leq SOC_{\max} \quad (8)$$

535  
536

#### 4. Simulation and performance evaluation

To evaluate the implementation of the proposed model and the MKEM, a residential distribution grid has been modeled using power system modeling tools: MATLAB, and GRIDLAB-D. GRIDLAB-D is a widely used open-source power-systems simulation tool. It was developed and maintained by the Pacific Northwest National Laboratory (PNNL) in the U.S [61], [62]. It has various objects and modules to analyze the electric power flow, residential load and energy management. Furthermore, it can simulate both single-phase and three-phase balanced and unbalanced systems, with distributed customers [62]. GRIDLAB-D includes models of various distribution system components and can also be combined with other simulation tools such as: MATLAB or NS3 [63], [64].

To demonstrate the effectiveness of the proposed model and enhance the roles played by actors within a micro-grid, the effect of RESs' penetration has been analyzed. In that regard, the modified version of the IEEE 13 Node Test System has been used to show the effect of integration of PV systems into the grid. IEEE 13 Node Test System has been modified to integrate lights, power loads and ZIP load models. Moreover, smart appliances such as multi-state physical load models of the HVAC and water heaters have been used. Furthermore, the Typical Meteorological Year data (TMY2) of WA-Seattle has been used for weather data [65]. Overall, the size of both renewable energy sources and energy storage systems depends on the location and the weather used in the simulation. Subsequently, the outcome of the simulation setting provided a 13-node test system with a total of 1247 single-family residences. Each residence has been equipped with a water heater, a HVAC, ZIP models of different appliances and triplex meters to measure the required data. Furthermore, for each residential home, a controller has been used to control the smart appliances such as the water heater and HVAC. These controllers are known as transactive controllers and can interact with the market using price information [66]. In this context, a local double-auction market has been used. In a double-auction market, bidding is done from both the market players i.e. customer and provider. Hence, a double-auction market uses a two-way communication strategy where both buyers and sellers have an opportunity to reach a transaction. In this regard, the market operator collects, buys and sells bids to clear a double auction, then finds a common cleared market price and quantity and broadcasts this information back to the participants. As a result, the existence of a double-auction market enhances the involvement of buyers and sellers in defining the suitable price and quantity of electricity.

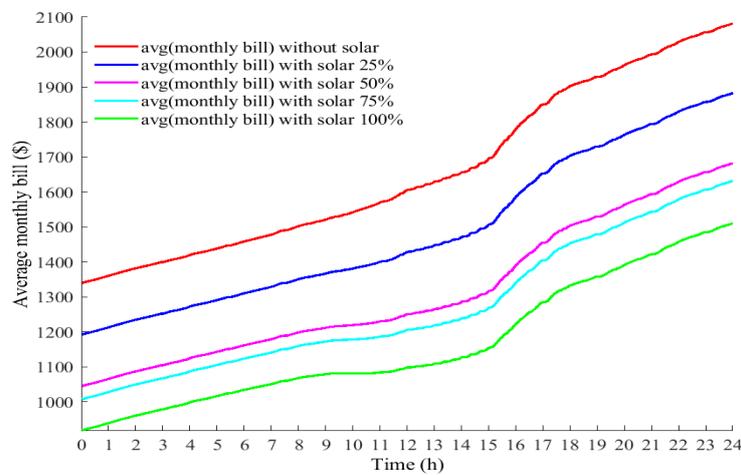
570 In addition, given the proposed model, electric loads connected at each node and voltage at  
571 the substation, a power flow calculation has been performed to determine the steady state node  
572 voltages and line currents at each point of the system. In this article, Newton-Raphson has been  
573 used. Among the various numerical methods used for solving the power flow problem, Newton-  
574 Raphson iterative method is the most widely used, since it is more reliable, and the number of  
575 iterations required for convergence is independent of the power system size [67], [68].

576 Moreover, in the proposed model, one node is designed as a swing or slack bus. This node  
577 represents an infinite bus and provides the fixed voltage reference for the solver iterations.  
578 Furthermore, the scenario that used for the simulation is the integration of power generation  
579 units consisting of solar into the grid using a virtualization of the proposed micro-grid model.  
580 Energy demand and cost have been evaluated under different PV penetrations. Moreover,  
581 analysis have been made to show the impact of RESs on energy cost, energy losses and energy  
582 demand. The power factor control of the converter was enabled to operate at a constant power  
583 factor. In addition, the inverter efficiency was defined as 94% and the rated power for a one  
584 inverter was defined as 25 kVA. Moreover, the inverter is assumed to provide ideal maximum  
585 power-point tracking, capable of converting the maximum power from the solar installation.  
586 When the inverter is controlled to produce less than this power, it is assumed the PV system is  
587 loaded to supply this power and the possible power output of the panel is not fully reached. In  
588 this regard, the inverter controls the power flow from the PV and the selected control mode  
589 'CONSTANT\_PF' defaults to only generating real power, transiting all the available energy  
590 produced by the solar PV installation onto the grid. In this simulation, the PV penetration in the  
591 virtualized micro-grid has been measured by summing the power rating of all PV systems used  
592 in the residential power system. Indeed, the surface area of the PV system was defined as 5382  
593 ft<sup>2</sup> and the daily insolation level that the cell was rated for was defined as 4 kW/h.

594 This article has focused on introducing BESS to improve the key issues of several problems  
595 that have been introduced after RESs integration into the grid and perform peak-shaving. Using  
596 GRIDLAB-D to simulate a summer residential load profile, combination of BESS and PV has  
597 been analyzed to provide the most effective mitigation of restricting issues under high PV  
598 penetration. Therefore, to enhance their role in energy management; batteries have been used  
599 with inverters. Each inverter was linked to a triplex meter. Moreover, a double-auction retail  
600 market has been implemented and augmented with a Real-Time Price (RTP) for bill mode to  
601 enhance demand response and customer participation in energy management. In this sense, the  
602 market can accept demand, supply bids and clear on five-minute intervals. In addition, it can  
603 also be designed to manage capacity constraints at substations.

604 The simulation was run for one month, and weather condition of August from TMY data  
605 regarding WA-Seattle has been used [65]. In addition, the preheating mode for HVAC was  
606 eliminated.

607 Fig. 7 shows the impact of PV on energy cost. It compares the system with and without solar  
608 power generation units on a sunny day and shows the effect of introducing different capacities  
609 of PV systems (25%, 50%, 75% and 100%) on the monthly bill consisting of the purchased  
610 energy price per month. As can be seen in Fig. 7, the accumulative monthly bill, collected by  
611 triplex meter (and meters) is reduced when a high PV penetration is integrated. It provides end-  
612 users with the financial incentives to increase PV penetration, leading to a considerable  
613 reduction in monthly bill as shown in Fig. 7.



614 Fig.7 Monthly bill with varying PV penetrations, on a sunny day.  
615  
616

617 Moreover, the integration of RESs reduces transmission losses. RESs have the capacity to  
618 retain the energy loss at a minimum level. The Fig.8 shows power losses through the  
619 transformer under different PV penetrations. Significant energy loss reduction can be achieved  
620 for this scenario with high PV penetrations. Note that the fluctuation in the power losses is  
621 associated with the agent-based simulation, the agents such as consumers, producers, or grid  
622 operators, which are the decision-making entities and the main interconnections between the  
623 different flow networks, try to reduce power losses and interact with the environment that  
624 evolves over the time [69]. Therefore, the environment is affected by the agents, leading to a  
625 small fluctuation [70]. Indeed, the demand response strategy used by end-use customers  
626 modifies the normal consumption patterns in response to incentives from grid operators along  
627 with the fluctuations of high penetration of PV systems [71].

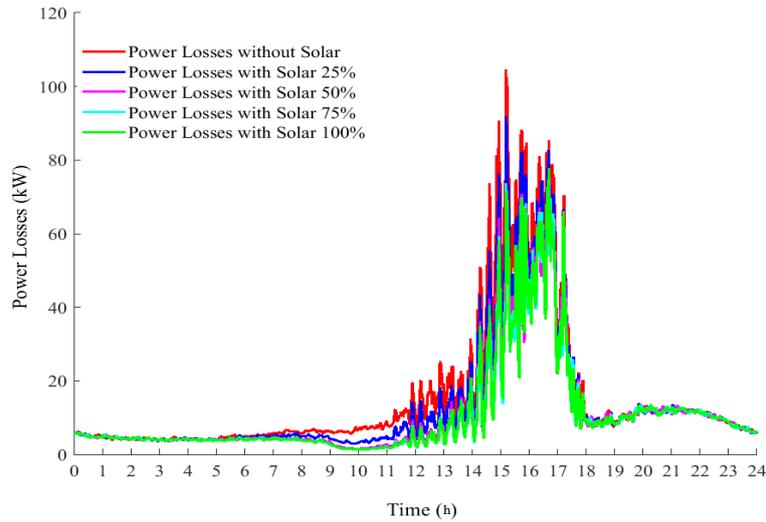


Fig.8 Transformer Power losses with varying PV penetrations, on a sunny day.

However, the integration of high PV penetrations into the system induces some disturbances and issues on the distribution level. In the following, issues related to PV integration into the micro-grid are discussed based on the use cases presented in Table 1.

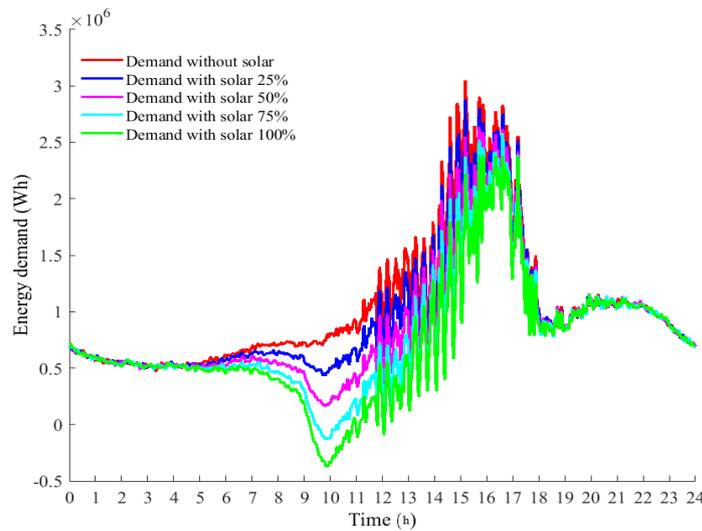
Table 1. Studied use cases

Use cases
Integrating different PV penetrations
Integrating 75% PV penetration and ESS
Integrating 50% PV penetration and ESS
Integrating PV with different PV efficiencies
Integrating PV with 0.15 PV efficiency and ESS

### 1) Back-feeding

Rapid introduction of solar panels impacts the energy demand curve. This impact is most obvious during the middle of the day when the irradiation is at its highest and leads to a substantial demand reduction as shown in Fig. 9. Capacities at 75% PV penetration and greater than 75% PV penetration resulted in PV back-feeding to the main grid during peak radiation times. However, the night peak load remains unchanged even with high PV penetration due to lack of irradiation. The Back-feeding occurs when PV generation exceeds demand and losses on a feeder. In this regard, integration of Renewable Energy (RE) systems causes reverse power flows, i.e., feeding back into the grid as they are generally connected near the load center. However, under high penetration of distributed generation, this issue may cause local overvoltage in the distribution grid [72]. Besides that, Fig. 9 shows fluctuation in the energy demand, derived from using a double-auction market with demand response strategy, the RTP

649 billing mode where prices are varied every 5 minutes and demand pattern. The variation in the  
 650 electricity price leads to the sustained undamped fluctuation in the system [73]. Indeed, the  
 651 demand response strategy could lead to such fluctuation as explained in [74], [75]. Moreover,  
 652 the output power fluctuation of RESs due to the dependency of these sources on weather  
 653 conditions could cause such oscillation in the energy flow [76]. In this regard, the fluctuation  
 654 of electricity prices due to the RTP billing mode along with the consumption's dependency on  
 655 the electricity price and RESs output power lead to the fluctuation in the energy demand. In the  
 656 following, effective management of PV integration to mitigate this issues and tackle Back-  
 657 feeding problem has been pointed out.



658  
 659 Fig.9 Energy demand of the micro-grid in different PV  
 660 Penetration scenarios, on a sunny day.  
 661  
 662

663 In that regard, the increasing penetration of solar generation imposes challenges on the  
 664 existing distribution infrastructure inducing shifts in peak demand. As the percentage share of  
 665 generated PV energy is increasing in the total energy basket, it is necessary to integrate energy  
 666 storage with PV. Combining solar PV with energy storage can provide an effective solution for  
 667 regulating the load. This combination will have a positive impact on consumers, utilities and  
 668 communities by means of effective cost, improved reliability and power quality. Furthermore,  
 669 integrating PV with storage systems provides potential benefits to the grid, such as peak  
 670 shaving, load shifting, load leveling, voltage and frequency regulation, outage protection, and  
 671 other ancillary services. In this regard, to achieve the above benefits, the existence of energy  
 672 storage in the presented scenario is mandatory to allow storing solar energy, mitigating back-  
 673 feeding and using the stored energy at high energy prices.

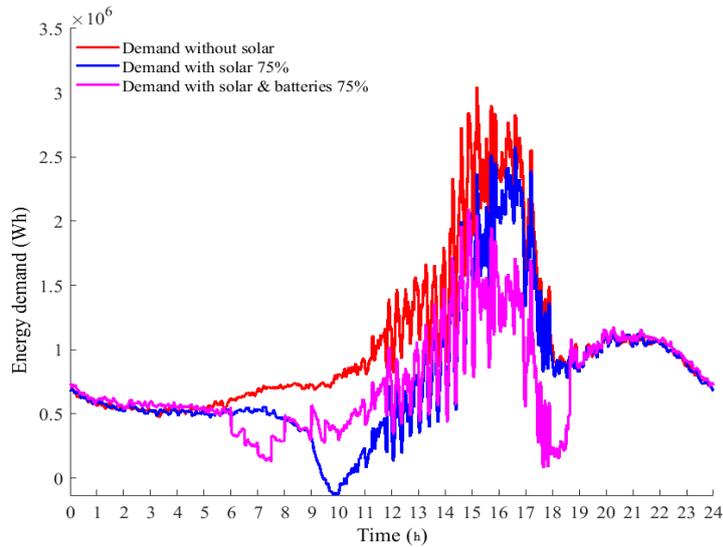


Fig.10 Energy demand of the micro-grid with, and without 75% PV penetration and BESS on a sunny day.

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675  
676  
677

678 Therefore, using a virtual system of the proposed micro-grid, batteries have been  
679 implemented on each transformer triplex meter. In addition, residential houses obtain the power  
680 from three sources; the power grid, the rooftop solar panel and the battery which is charged  
681 from solar power generation units in the middle of the day, when the sun is at its peak. The  
682 battery can also be charged from the power grid during off-peak hours. Fig. 10 shows the effect  
683 of integrating battery systems into the grid. The PV back-feeding has been removed by the  
684 introduction of BESS for 75% of PV penetration. Moreover, in Fig. 11, these systems regulate  
685 the demand of energy and contribute to load shifting and peak shaving for 50% of PV  
686 penetration. Hence, when using batteries, the demand of energy shifts into a more suitable  
687 operating region.

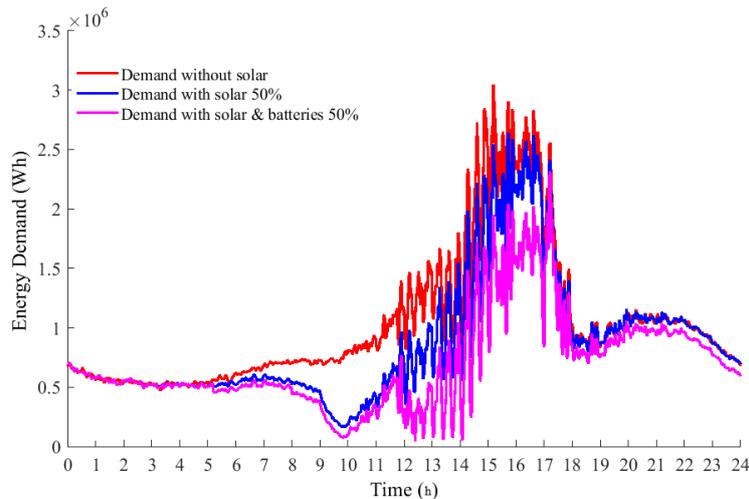


Fig.11 Energy demand of the micro-grid with 50% PV and BESS on a sunny day.

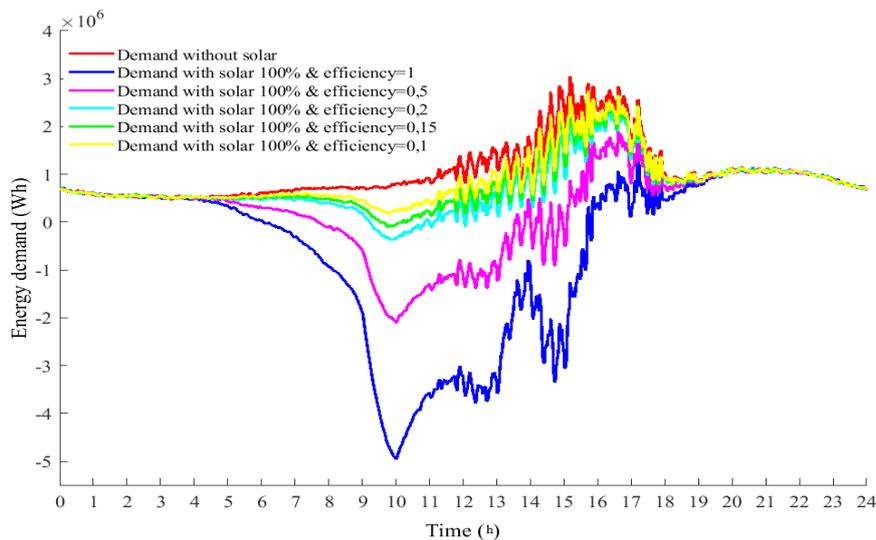
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692 2) Intermittent Power due to the components' Efficiency

693

694 Non-renewable sources are known as reliable and controllable sources, generating a known  
695 amount of energy. However, RESs do not generate a stable energy quantity and are influenced  
696 by various parameters. For instance, the performance of solar panels depends on the quantity  
697 of sunlight, efficiency, air density, temperature and other factors. Moreover, PV parameters are  
698 derived from a physics-level perspective. The area, efficiency, panel type and orientation,  
699 power production models, all these parameters are used to determine how this installation can  
700 generate energy as the solar conditions change throughout the day due to the weather  
701 conditions. Subsequently, the main challenge in using RESs is their intermittency and stochastic  
702 behavior [77].

703 Besides that, solar panels need to absorb sun rays to generate electricity. Thus, the panels  
704 should have the best efficiency and face for the best direction to maximize generation of energy.  
705 Therefore, it is essential to determine the correct size of the PV to satisfy the energy demand.  
706 This can be performed by considering the efficiency of power conversion from the solar  
707 insolation to DC power and the maximum power output of solar. In addition to the previous  
708 requirements, supporting devices such as inverters with effective controls are needed to allow  
709 better management of the produced energy. In this paper, the proposed model has been  
710 implemented using 100% PV penetration and different values of solar efficiency. As shown in  
711 Fig. 12, high efficiencies have an apparent negative effect on the entire grid.



712

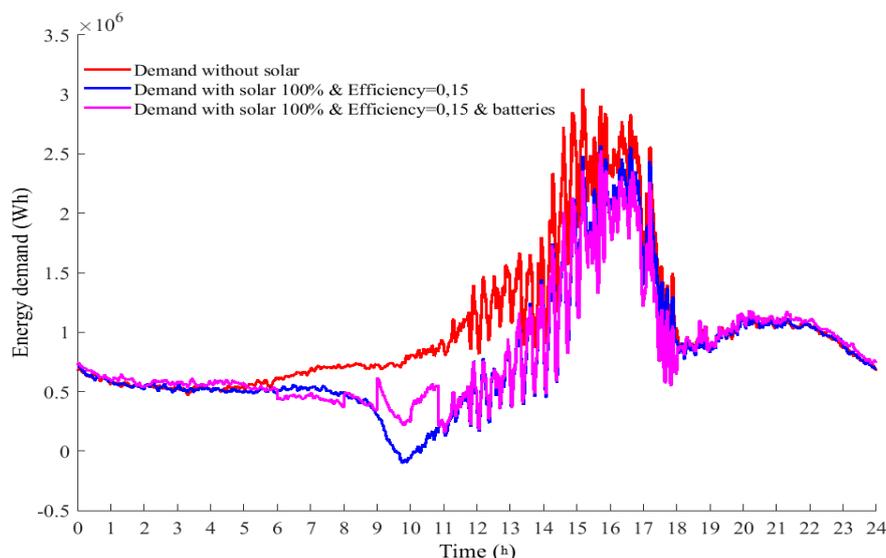
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714

715

Fig. 12 Energy demand of the micro-grid varying PV efficiency, on a sunny day.

716 Moreover, the efficiency at “0.15” and greater than “0.15” induce significant demand  
717 reduction during peak hours. In Fig. 13, the intermittent power issue has been removed by  
718 integrating the optimal size of BESS under an efficiency of “0.15”.



719  
720 Fig. 13 Energy demand of the micro-grid with 0.15 solar efficiency and  
721 BESS on a sunny.  
722

723 As a result, the virtual system of the proposed micro-grid model provided a normal behavior  
724 once power generation units consisting of solar energy, integrated into the grid. The local ESS  
725 modeled in the proposed architecture, designed in the proposed MKEM and implemented in  
726 the virtual system performed its role. Consequently, the integration of RES and BESS in power  
727 systems has beneficial effect; this integration not only contribute to the reinforcement of the  
728 distribution networks and reduce power losses, but also perform peak shaving, load shifting,  
729 and reduce energy cost.

730

## 731 5. Conclusion

732

733 In this article, a smart grid architecture was presented by means of System of Systems (SOS)  
734 technique. The proposed architecture integrated several micro-grids and nano-grids, known as  
735 small residential power systems with renewable sources, battery storage, and domestic load.  
736 Such integration can increase the complexity of system modeling. By employing a micro-grid  
737 key element approach, this article tried to address the system complexity. Moreover, the  
738 integration of renewable power generation units was analyzed and investigated by virtualization  
739 of the introduced architecture through MKEM approach to test system stability. The system  
740 was analyzed under various PV penetrations with different PV efficiency to demonstrate the  
741 effectiveness and performance of the proposed framework, as well as the employed approach.

742 The result showed that the proposed model could reduce energy cost and power losses.  
743 Moreover, the proposed framework addressed the dependency of renewable power generation  
744 units on weather condition by utilizing energy storage systems to reduce and control the  
745 fluctuation of such distributed generations. Indeed, ESSs acted as not only load but also as  
746 generation to shift and bring down the power flow. Furthermore, in this article, it was  
747 demonstrated that the MKEM can effectively be utilized as a robust approach for reliability  
748 study, outage detection, advanced control, demand response, advanced metering infrastructure  
749 and storage management.

750 Hence the present article proposed a smart grid architecture to provide beneficial  
751 opportunities for grid-friendly deployment of ESSs in smart grid systems. Nevertheless, the  
752 following limitations need to be addressed in future studies:

- 753 • Since battery energy storage systems have a significant impact on the total operation  
754 cost and the life-time of the battery reduces during charging and discharging cycles,  
755 the degradation cost of battery should be considered as a target in cost-effectiveness  
756 analysis.
- 757 • Vehicle electrification has recently drawn considerable attention which raises  
758 concern about bi-directional power flow besides vehicle-to-grid and grid-to-vehicle  
759 functionalities that need to be assessed.
- 760 • As recent studies focus on technical and economic aspects of PV-battery systems,  
761 further investigations are merited in terms of voltage deviation and total cost of  
762 investment in such technologies by studying weighted multi-objective functions.

## 763 ACKNOWLEDGEMENTS

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765

## 766 6. References

767

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