

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**

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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].

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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.

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

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- 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.

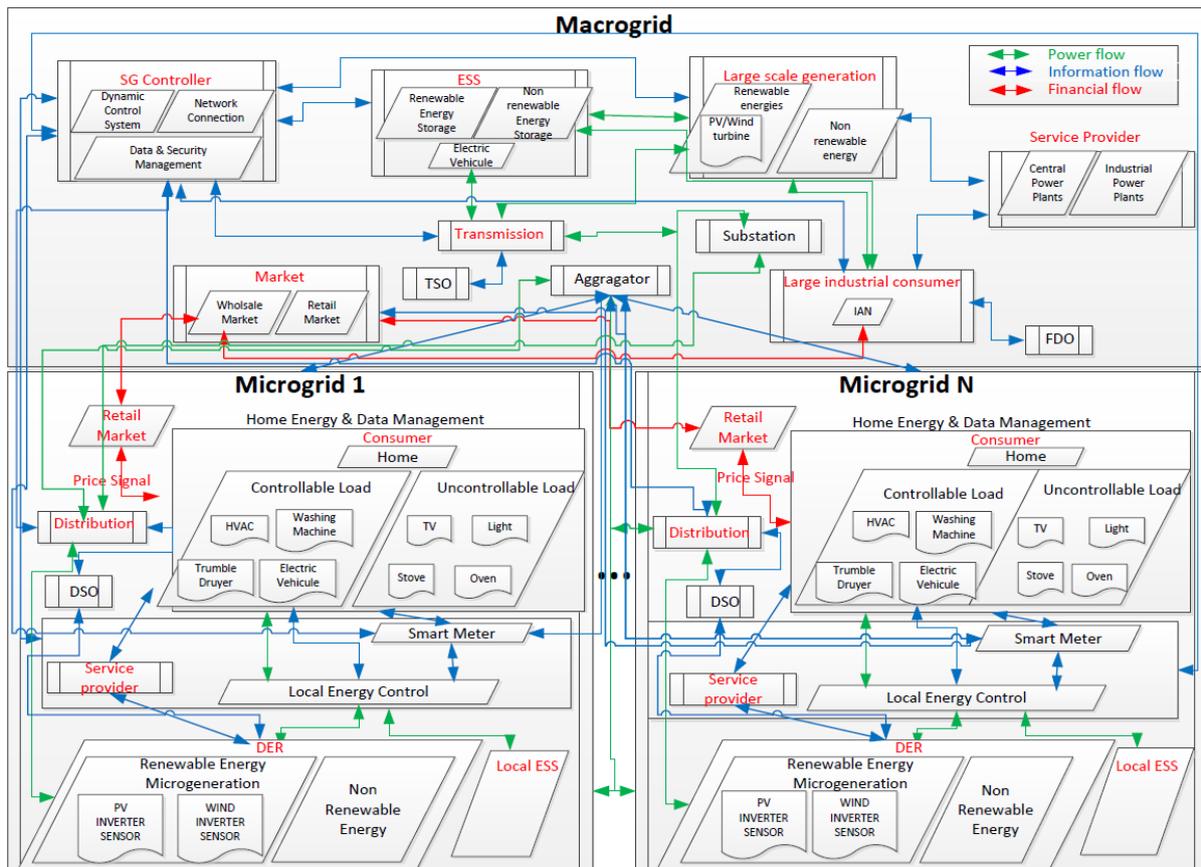


Fig.1 The proposed Smart Grid Architecture.

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).

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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:

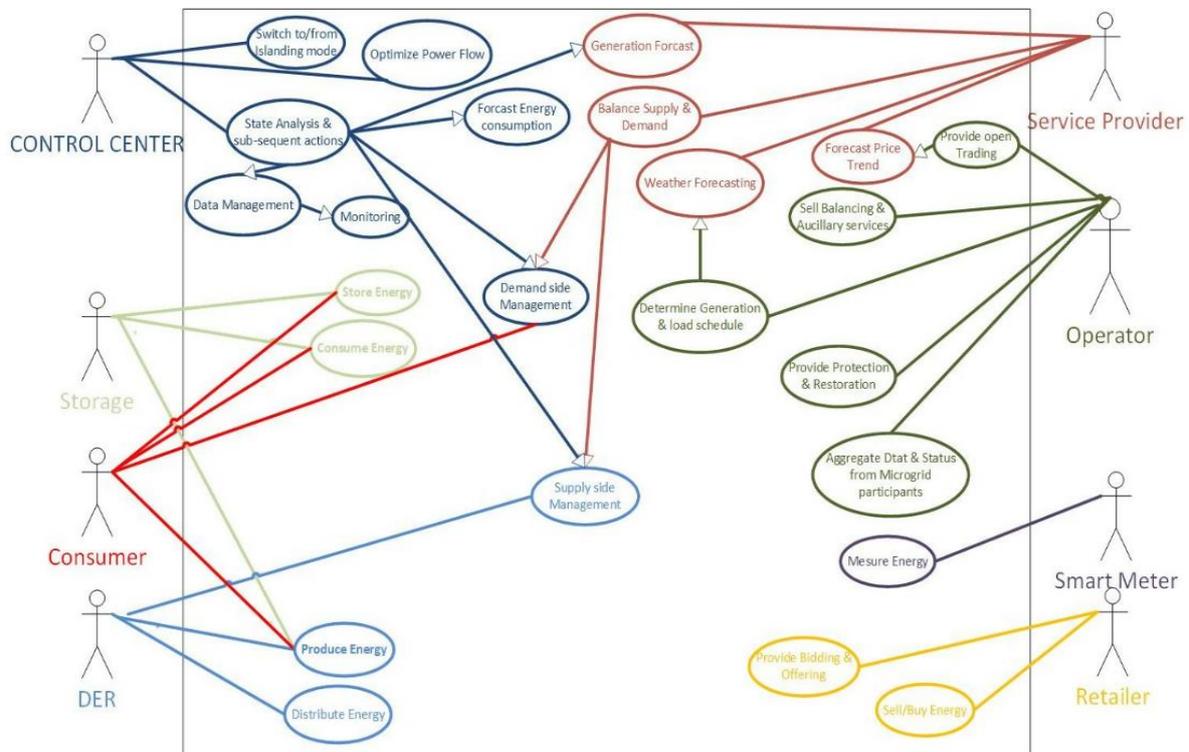
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$$314 \quad \sum P_{loads} = P_{pv} + P_{ESS} + P_{market} \quad (1)$$

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.



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 344
 345
 346
 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):

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

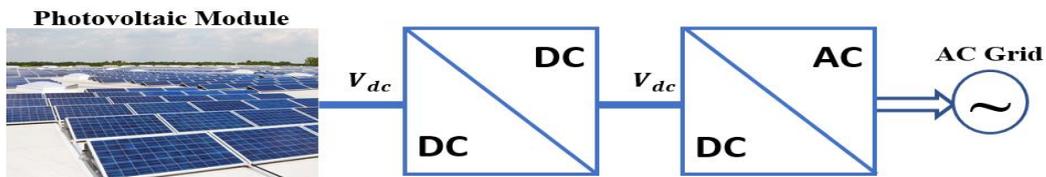
402
 403 where P_n is nominal power of PV system at reference conditions, R is solar irradiance, R_{ref} is
 404 solar irradiance at reference conditions, K_t is temperature coefficient of PV systems, T_c is
 405 temperature of PV system °C, T_{ref} is temperature of PV system at reference conditions,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

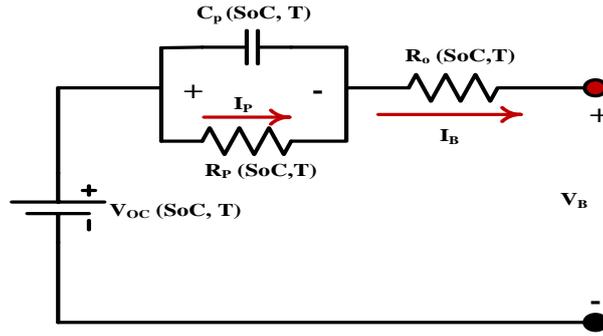


Fig.4 Battery model.

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:

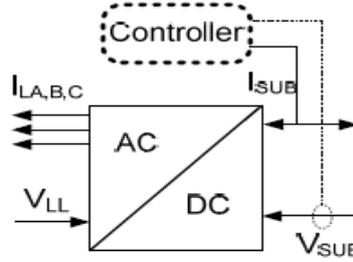


Fig.5. Block diagram of inverter model.

521
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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.

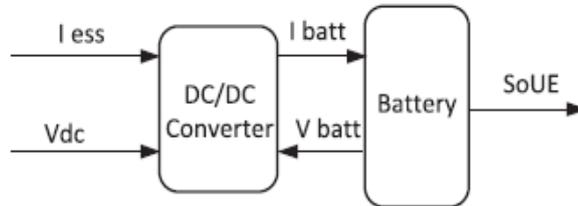


Fig.6. Battery based ESS model [60].

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.

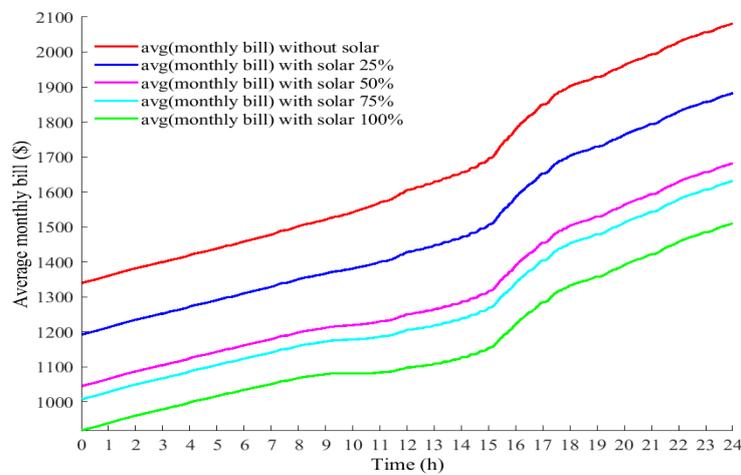
570 In addition, given the proposed model, electric loads connected at each node and voltage at
571 the substation, a power flow calculation has been performed to determine the steady state node
572 voltages and line currents at each point of the system. In this article, Newton-Raphson has been
573 used. 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 ft² 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
615 Fig.7 Monthly bill with varying PV penetrations, on a sunny day.
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].

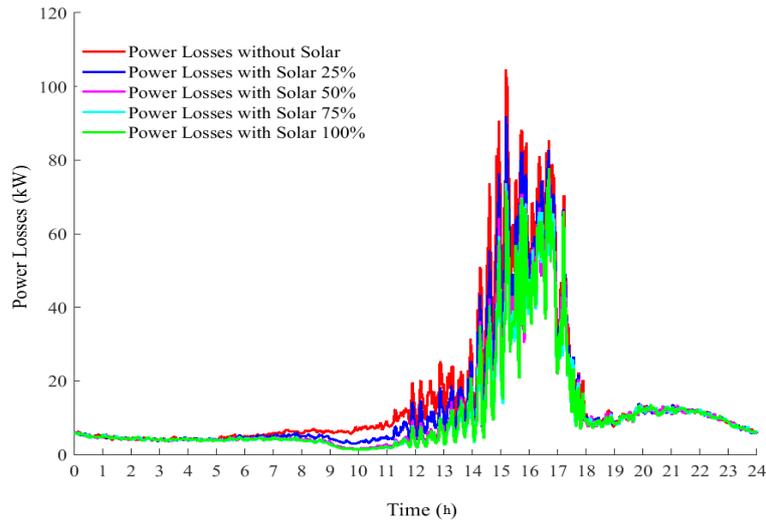


Fig.8 Transformer Power losses with varying PV penetrations, on a sunny day.

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.

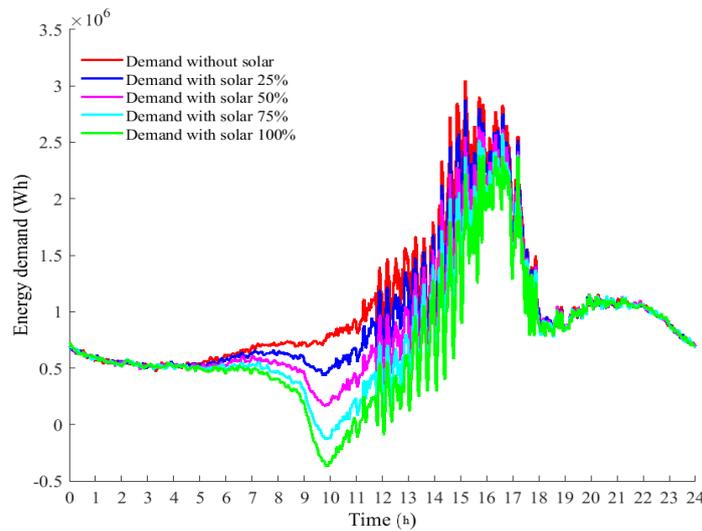
Table 1. Studied use cases

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.

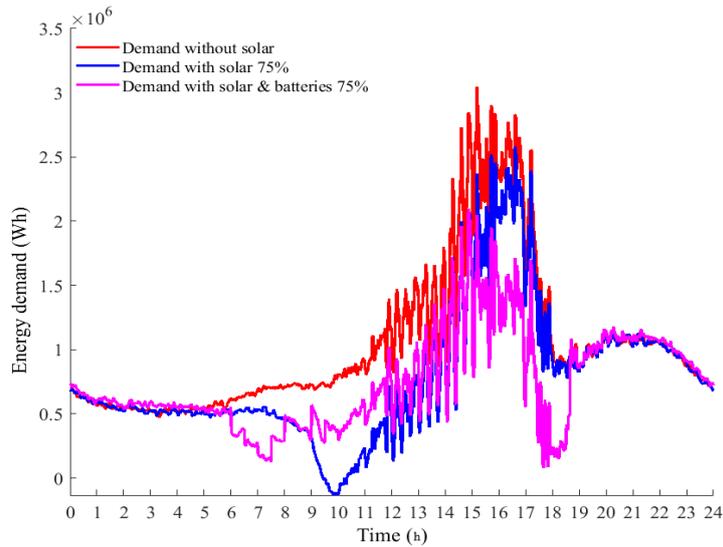


Fig.10 Energy demand of the micro-grid with, and without 75% PV penetration and BESS on a sunny day.

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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.

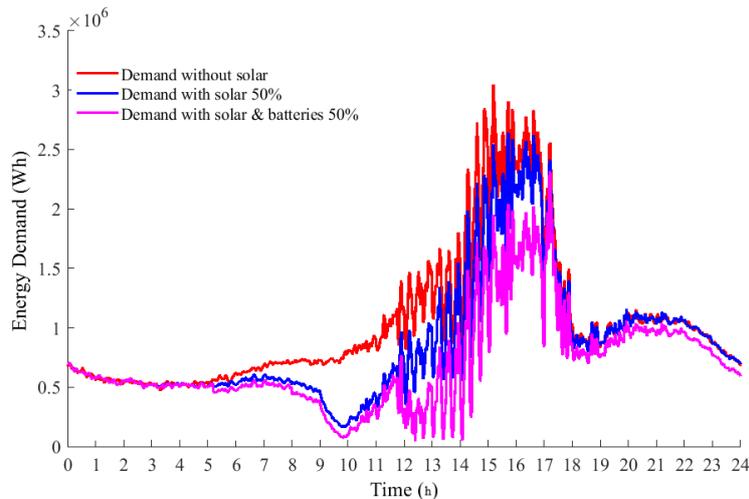


Fig.11 Energy demand of the micro-grid with 50% PV and BESS on a sunny day.

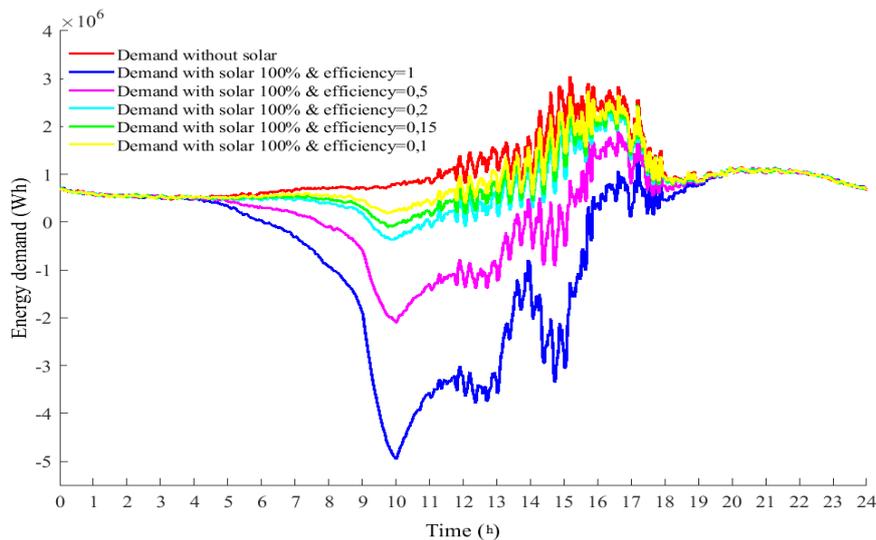
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692 2) Intermittent Power due to the components' Efficiency

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

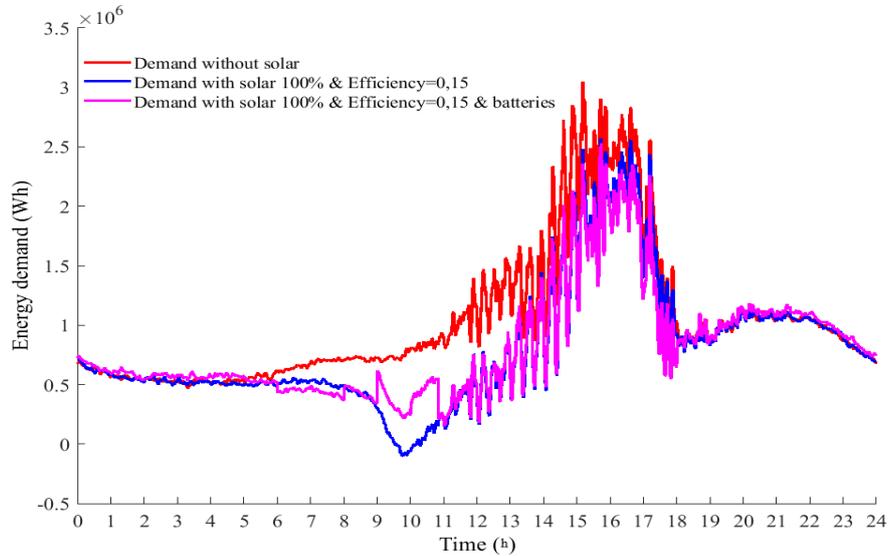
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714

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.

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765

766 6. References

767

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