Impact of Peak-Time Power Shortages on Thermal Comfort in Kuwaiti Homes: Toward a Cyber-Physical Energy Testing Framework

Abdalrahman Alajmi, Mohamad Rida, and Nick Kelly

Abstract Power outages during peak hours in Kuwait can seriously impact the comfort of indoor spaces, especially during the intense summer heat. When cooling systems go offline, even for a short time, indoor temperatures can rise quickly, making homes uncomfortable and potentially unsafe. This study looks at how these energy limitations affect thermal comfort inside buildings and proposes a cyber-physical energy assessment framework aimed at improving energy efficiency while reducing discomfort during critical periods. We examine household temperature conditions, adaptive comfort techniques, and real-time power usage data using a mixed-method approach. Results show that outages during peak hours cause extreme heat stress, which causes residents to use ineffective cooling techniques. To help buildings better cope with power outages, the proposed cyber-physical framework brings together energy management systems, smart sensors, and predictive modeling. By combining these elements, the study aims to strike a balance between keeping occupants comfortable and using energy more efficiently. It also offers practical insights that can benefit homeowners, energy planners, and policymakers looking to make buildings more resilient and sustainable in challenging climates. This study highlights the urgent need to adopt smart energy solutions that can improve everyday living conditions in Kuwait while also addressing broader challenges related to long-term energy sustainability.

Keywords Cyber-physical systems · Thermal comfort · Residential cooling · Kuwait

A. Alajmi (✉) · M. Rida · N. Kelly
Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, Scotland, UK
e-mail: Abdalrahman-r-e-s-r-alajmi@Strath.ac.uk

M. Rida
e-mail: M.rida@strath.ac.uk

N. Kelly
e-mail: nick@esru.strath.ac.uk

© The Author(s) 2026

M. Trabelsi et al. (eds.), *Proceedings of the 2nd Symposium on Smart, Sustainable, and Secure Internet of Things*, Lecture Notes in Electrical Engineering 1513,
https://doi.org/10.1007/978-981-95-5136-1_19

1 Introduction

1.1 Energy Problem in Kuwait

Kuwait is an arid country, which means that the climate is extremely hot during the summer season, reaching up to 50 °C, so it is no wonder that the major dependence is on mechanical air conditioning [1]. Because of its geographical location in the Arabian Gulf region, the country experiences a long summer period, with average temperatures between 45 and 50 °C [2]. Extreme weather conditions call for the use of AC systems not as a luxury but as a necessity, thus increasing energy demand greatly.

1.2 End-Use Energy in Buildings

Kuwait Cooling, which accounts for more than 60% of the electricity used in Kuwait's buildings [2], significantly strains the national grid, particularly during the summer when peak demands exceed 17,000 MW [3]. Factors contributing to this high demand include extreme temperatures, inefficient building standards, and low electricity prices that discourage conservation [1]. The rapid growth of high-rise buildings, especially in urban areas, further escalates cooling needs. There are also measures such as the implementation of higher standards for building codes to improve insulation and passive cooling [4], smart thermostats usage, and renewable energy, in particular, solar cooling systems [5]. It's important to note that simply changing the thermostat settings from 21 to 24 °C could reduce the cooling load by 10% [5]. As for the long-term perspective, the mentioned strategies imply the focus on energy-saving buildings, smart cooling technologies, and renewable electricity sources capable of meeting the demand without overloading Kuwait's environment.

1.3 Kuwait's Cooling Challenges and Power Demand

In June 2024, Kuwait, for the first time, had a scheduled load shedding, and this action happened despite the country's energy surplus. Increased electricity usage due to the scorching heatwaves that were experienced made the government turn off the power for one to two hours intermittently in different districts across the country. These outages imposed much thermal stress on the residents and also raised concerns as to the reliability of the national grid. To avoid total blackout along the streets, authorities came up with official conservation measures, expecting the citizens to use less energy during the peak hours of the day between 11 am and 5 p.m. [3]. The continuous rise in the consumption of electricity means an urgent need for Kuwait to develop demand side management (DSM) to address the stability of the power sector.

Out of information gotten from the Ministry of Electricity, Water, and Renewable Energy in Kuwait, it was revealed that Kuwait's peak demand in 2024 was 17,640 and 18,569 MW is the expected peak demand in 2025, implying a yearly increment of about 1000 MW. If this trend persists, there may be periodic problems, such as load shedding or frequent disruptions of the power supply, especially during the hot summer seasons. Rising energy consumption makes it imperative that a load control system is designed for a smart grid that can aim at improving distribution in the grid. Such problems as overloaded networks, therefore, require both technological solutions and policy actions in order to address the issue of a sustainable and reliable electricity sector in Kuwait.

1.4 Influence of Set-Point Reduction on Energy Use and Thermal Comfort

One practical way to reduce cooling energy use is by adjusting thermostat set-points. For instance, raising the temperature from 21 to 24 °C can cut energy consumption by around 10%. However, this energy saving often comes at the cost of occupant comfort [5]. As indicated by the Predicted Mean Vote (PMV) index, higher set-points result in "slightly warm" PMV zones, but passive cooling strategies and approaches may mitigate the perceived discomfort. Studies have indicated that just improving insulation may reduce peak indoor temperature by 3 °C or greater, provided that cooling services are interrupted [4]. As shown in Table 1, set-point adjustments alone yield energy savings of 10%, which is not enough because its correlation with comfort is related, while insulation approaches achieve 12% energy savings and a moderate comfort rating. The most favorable approach is a combination of both, producing 20% energy savings while yielding an acceptable PMV value of − 0.2. This discussion places value on information-rich, real-time, cyber-physical energy systems within smart meters to adjust consumer cooling strategies and outdoor ambient conditions to balance energy efficiency with occupant well-being or comfort.

Table 1 Key strategies and their respective impacts on cooling energy consumption and thermal comfort

Strategy	Cooling energy reduction (%)	PMV score (comfort level)
Set-point adjustment	10	− 1.5 (less comfortable)
Insulation only	12	− 0.5 (moderately comfortable)
Combined strategy	20	− 0.2 (acceptable comfort)

2 Literature Review

2.1 Cyber-Physical Energy Systems (CPES)

The Fourth Industrial Revolution, commonly referred to as Industry 4.0, has brought about integrated intelligent systems, and CPES is at the center of energizing the energy sector [6]. Big data, Digital twin, or AI and decision-making systems have advanced the aspects of energy efficiency in smart grids, smart buildings, and Industrial energy management as espoused by Industry 4.0 standards [7]. CPES within Industry 4.0 has the feature of cyber-physical feedback, where power over certain assets is regulated and adjusted based on the outputs of physical sensors [8]. In the context of Kuwait, where there is high energy demand, this capability is effective in:

- Smart HVAC optimization
- Predictive maintenance for power grids
- Decentralized energy control.

In this way, through using the cloud, computing, and edge analytics, CPES optimizes energy flexibility while also strengthening the power grid performance and mitigating carbon emissions. Smart meters and cyber-physical testing platforms are essential in enhancing the effectiveness of building energy since the cooling load accounts for major electricity consumption in Kuwait [9].

2.2 Challenges and Research Gaps

Despite its strong potential, the implementation of the CPES framework in Kuwait faces several barriers: technical, economic, and regulatory. One of the key technological challenges is the lack of well-established communication protocols that can effectively link modern components like smart grid infrastructure and IoT devices with older, conventional systems. This disconnect makes it difficult to achieve seamless integration, which is essential for a fully functional and responsive cyber-physical energy system [10]. This inhibits smooth flow, synchronization, and coordination in real time. In the same regard, the susceptibility to cyber threats is a concern because cybercriminals can attack smart grid or IoT controllers to hinder energy processes. This is because it is capital-intensive, requiring investment in smart sensors, AI-driven controllers, and energy storage systems [11]. However, the barriers are the highly subsidized electricity prices, which discourage consumers from adopting smart energy technologies. It is also important to understand that several regulatory gaps slow the deployment of CPES. Insufficient policies hinder investments, and ineffective implementation of energy efficiency standards hinders the adoption of smart cooling solutions [12]. The absence of proper building energy codes adds to the country's high energy consumption [8]. To the best knowledge of the present authors, there are no prior studies done to investigate the effectiveness of CPES for

Kuwait's conditions regarding cooling requirements. Future research should target specific cooling systems that are cyber-physical, improved cyber security protocols, and cheap demand-side management strategies. By addressing the identified challenges, it will be possible to advance Kuwait to harness the benefits of CPES for long-term energy stability, improved and more reliable grid infrastructure, and climate-responsive solutions.

3 Methodology

3.1 Building Geometry

This study is built around a residential building model that reflects the typical design found across Kuwait's housing infrastructure. The model incorporates key elements such as building geometry, construction materials, and occupancy patterns to create a realistic and practical framework for analyzing energy use and evaluating cooling performance. The summary of the thermal and structural parameters of the building model adopted in the analysis, as presented in Table 2.

This specific building model serves as a benchmark for energy simulations, helping to evaluate its cooling needs, thermal comfort levels, and overall energy consumption within the context of Kuwait's harsh climate.

Table 2 Key thermal and structural characteristics of the building model [13]

Characteristics	Value	Description
External wall U-value (W/m^2 K)	0.72	Plaster—AAC block 25 cm—plaster
Window construction U-value (W/m^2 K)	4.6	Double glazed
Roof U-value (W/m^2 K)	0.66	Tiles—cement—waterproof—foam concrete—concrete slab
Zone infiltration (ACH)	0.5	Air changes per hour
Total floor area (m^2)	412	Residential floor area
Number of floors	2 + roof	Two-story house with an accessible roof
Window ratio (%)	4.5	Window-to-wall ratio for daylighting
Occupancy density (person/total floor area)	6	Typical working family profile

Fig. 1 A typical Kuwaiti villa and it's ESP-r model [13]

3.2 Environmental System Performance (ESP-r)

To evaluate building performance in terms of energy, the ESP-r (Environmental System Performance) software is used. Many designers use ESP-r to assess the energy efficiency, thermal comfort, and Heating Ventilation and Air Conditioning (HVAC) system or Building Performance Simulation (BPS).

In this study, ESP-r is used to simulate real energy use by incorporating local climate data, occupant behavior, and HVAC system schedules. The tool allows for a detailed analysis by combining heat transfer modeling, airflow dynamics, and control algorithms. This makes it possible to evaluate how different cooling strategies affect both energy consumption and indoor comfort levels, giving a well-rounded view of building performance under Kuwait's climatic conditions. Figure 1 shows both the typical Kuwaiti villa and its corresponding ESP-r model. The simulation workflow includes:

- Identification of the building geometry (based on the model explained in Sect. 3.1).
- Evaluating the factors such as U-values for the construction materials, infiltration rates, and the properties of the glazing systems.
- Modeling and analyzing HVAC usage to determine energy consumption based on different thermostat settings.
- Introducing effective ways of forecasting cooling demand patterns while implementing energy conservation approaches.

3.3 The CPES Recommended Framework

This framework creates a smart bridge between a virtual building simulation and real-world HVAC equipment. At its core is ESP-r, a powerful building simulation tool that models indoor conditions like temperature and energy use. What makes this setup unique is how the simulation connects in real time with physical components such as a cooling unit, pumps, valves, and water storage tanks. The ESP-r model predicts needs like indoor temperature setpoints or comfort levels, then sends signals to the actual cooling system to take action. At the same time, real data from the physical

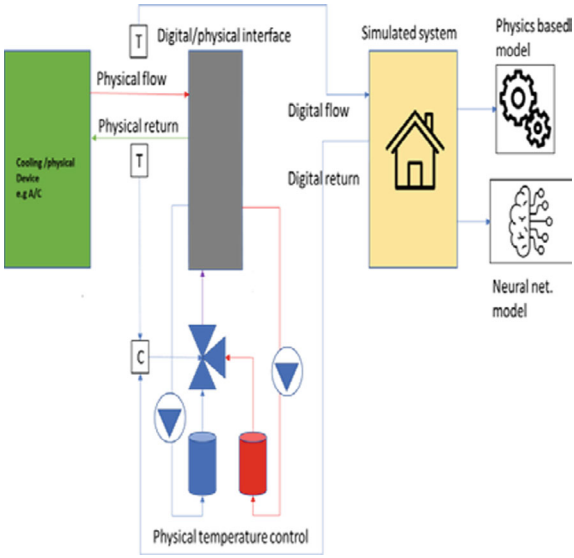

Fig. 2 General schematic of overall CPES

system like room temperature, flow rates, or tank levels is sent back to refine the simulation. This creates a continuous feedback loop, where the virtual and physical worlds stay in sync, allowing for smarter control, better comfort, and reduced energy waste.

The CPES framework integrates three essential components that work seamlessly together: a digital simulation model, a physical HVAC system, and an intelligent control interface. At the heart of the system is ESP-r, which acts as the brain, predicting how the building will behave under different conditions and determining the most efficient way to maintain comfort. These predictions are sent to the physical system as illustrated in Fig. 2, which includes real-world components like cooling units, pumps, valves, and water tanks that carry out the necessary actions. At the same time, sensors installed in the physical setup collect real-time data such as temperature and flow rates, which are fed back into the simulation to keep it aligned with actual conditions. Connecting everything is a control and communication layer that manages this continuous exchange of data, ensuring both sides stay in sync. This real-time feedback loop allows the system to adapt quickly and operate efficiently as conditions change.

3.4 The Integrated Approach of the CPES Framework

The CPES framework brings together simulation, physical modeling, and real-world control in a smooth, coordinated way. At the heart of this integration is a combination

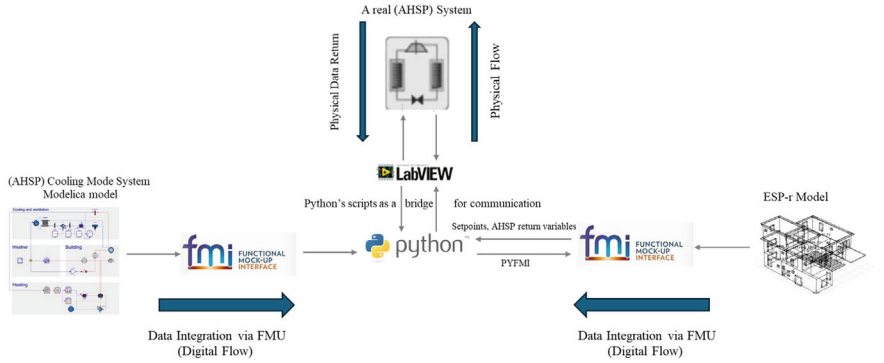

Fig. 3 Integrated approach methodology

of two powerful tools: The Functional Mockup Interface (FMI) for co-simulation, and Python scripting as the communication bridge that ties everything together.

As shown in Fig. 3, the system connects two simulation models the ESP-r building performance model and a Modelica-based cooling system using FMI as the standard for data exchange. While ESP-r focuses on how the building behaves thermally, the Modelica model simulates how the cooling system responds to different control inputs. These two models run side by side, exchanging important data like temperature setpoints and system responses through Functional Mock-up Units (FMUs). At the center of it all is Python, acting as the orchestrator. With the help of the PyFMI library, Python handles real-time communication between both simulation models, keeping them in sync as conditions change. It also interfaces with LabVIEW, which connects to the actual HVAC hardware gathering data from sensors and sending control signals to the system's actuators. This setup creates a smooth connection between the digital and physical parts of the framework, allowing them to work together seamlessly. By staying aligned with real-world conditions, the system can make smarter, real-time decisions. In Kuwait's extremely hot climate, this kind of adaptive control is especially important helping buildings maintain comfort while using energy more efficiently.

4 Results and Discussion

4.1 Thermal Comfort and Cooling Energy Load (ESP-r)

To understand how Kuwaiti's climate affects indoor comfort and cooling needs, an ESP-r simulation was run for typical residential building. Figure 4 shows how indoor temperature, cooling load, thermal comfort and relative humidity% change throughout the day, especially during a two-hour power cut from 14:00 to 16:00

which falls during peak demand hours. In Fig. 4a, it can be seen the relative humidity and the rise indoor temperature in both the bedroom and living room during the outage. With cooling disabled, the temperature quickly climbed from the set-point of 21 °C up to 32 °C. At the same time, thermal comfort measured by the PMV scale also worsened, reaching a value of 1.88 as illustrated in Fig. 4c. This clearly shows how quickly indoor conditions can become uncomfortable without cooling during extreme summer.

4.2 Energy Consumption and Thermal Comfort

The energy consumption analysis, illustrated in Fig. 5, shows a clear connection between thermostat set-point adjustments and overall cooling demand. The simulation reveals that even small changes to temperature settings can make a noticeable difference. For instance, increasing the set-point to 24 °C leads to a 14.4% reduction in cooling energy use highlighting just how effective temperature control can be in reducing electricity consumption. However, this energy saving comes at a cost. As expected, raising the set-point also increases the PMV (Predicted Mean Vote), suggesting a higher level of thermal discomfort for occupants. The study also explores short-term load reduction strategies, such as maintaining the set-point at 21 °C but introducing a two-hour power cut during peak hours. This approach eases demand on the power grid but results in only a 2.5% drop in total energy use, indicating that short-term interventions alone may not significantly improve efficiency. As shown in Fig. 5, temporary load-shedding might help reduce peak stress on the grid, but it doesn't offer a strong long-term solution. Further analysis using PMV, presented in Fig. 4c, confirms that while higher set-points do save energy, they can also lead to thermal discomfort. A PMV value of 1.88 reflects a noticeable feeling of warmth, which may affect occupant comfort, well-being, and productivity. These findings point to the need for hybrid cooling strategies combining passive design features, better insulation, and intelligent climate control to strike a better balance between comfort and energy efficiency. These findings also highlight the need for more advanced solutions such as the cyber-physical energy system framework explained in Sects. 3.3 and 3.4, passive design features, and smart automation to balance energy savings with occupant comfort in hot climates like Kuwait's.

5 Conclusion

The integration of Cyber-Physical Energy Systems (CPES) in Kuwait has been investigated in this study, with a focus on how these systems can improve grid stability, optimize building performance, and increase energy efficiency. The study has emphasized important discoveries about thermal comfort, cooling energy demand, and overall energy consumption through in-depth analysis using Building Performance

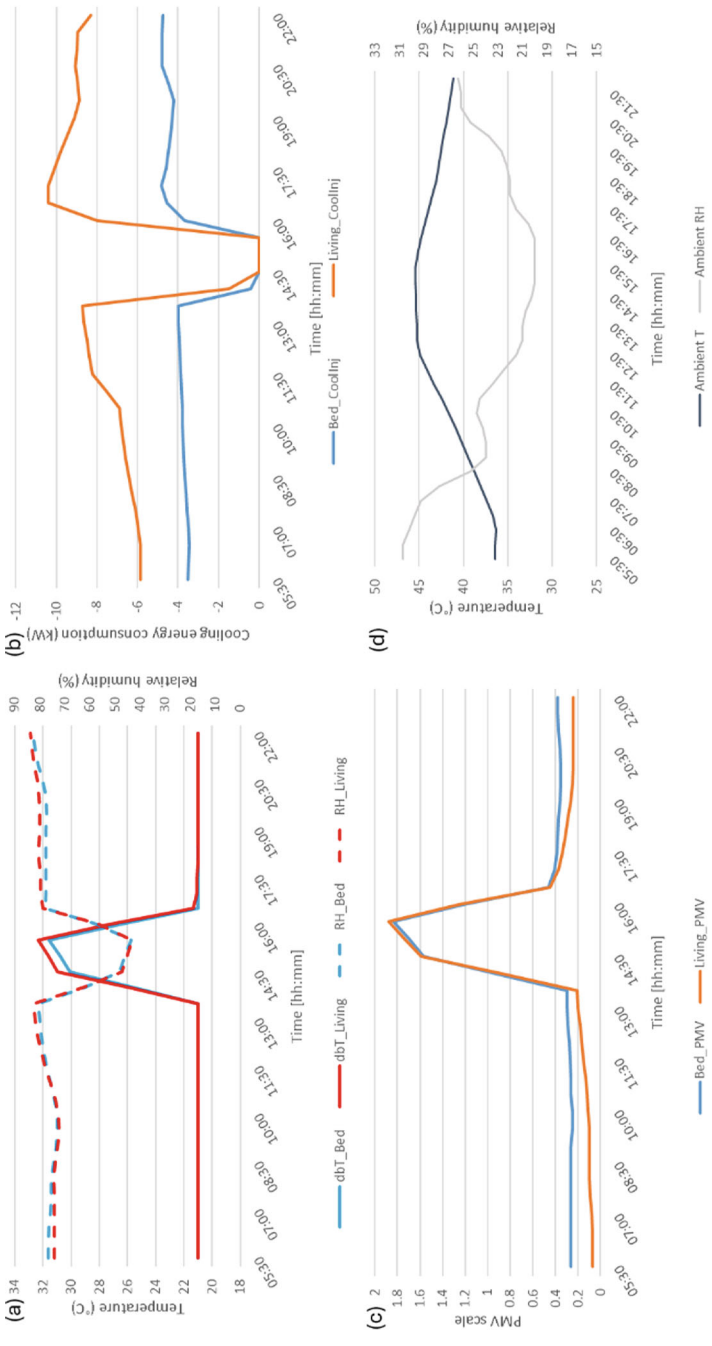

Fig. 4 Thermal comfort and cooling energy load–ESP-r analysis

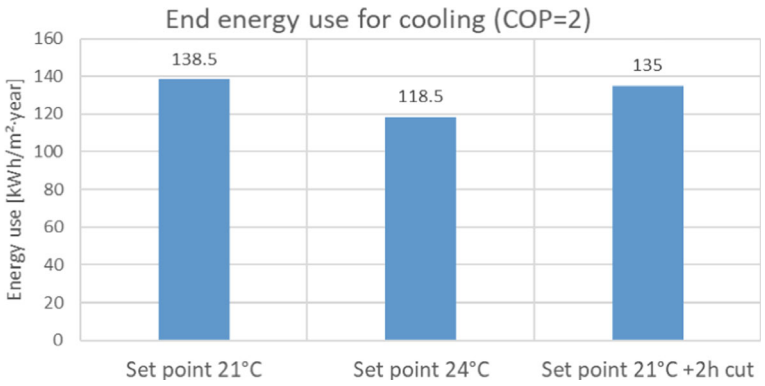

Fig. 5 ESP-r energy consumption analysis

Simulation (BPS) technologies like ESP-r. According to the findings, energy efficiency can be considerably increased while preserving tolerable comfort levels by making calculated adjustments like raising the cooling set-point or putting peak load reduction strategies into place. Future developments must, however, focus on crucial areas like blockchain-based energy transactions, renewable energy integration, and Smart Grid deployment if CPES is to reach its full potential. With the help of these technical advancements, Kuwait's energy system might become more resilient, sustainable, and able to adjust to the country's rising electricity needs. The effective implementation of these ideas will also depend on interdisciplinary research partnerships, investment in cutting-edge infrastructure, and governmental changes. To build a sustainable and energy-efficient future for Kuwait, this study emphasizes the necessity of a multifaceted strategy that incorporates technology innovation, policy adaptation, and consumer participation.

References

1. Kulaib A, Kalendar A, Hussain S, Alhendal Y (2021) A parametric study of the energy efficiency of existing air-conditioned buildings in Kuwait. J Green Build 16(1):163–178
2. Park J, Kim T, Lee CS (2019) Development of thermal comfort-based controller and potential reduction of the cooling energy consumption of a residential building in Kuwait. Energies 12(17):3348
3. MEW Kuwait (2024) Retrieved from https://www.mew.gov.kw/en/
4. Al-Rashed AA, Alnaqi AA, Alsarraf J (2021) Energy-saving of building envelope using passive PCM technique: a case study of Kuwait City climate conditions. Sustain Energy Technol Assess 1(46):101254
5. Al-Mulali U, Ozturk I (2014) Are energy conservation policies effective without harming economic growth in the Gulf Cooperation Council countries? Renew Sustain Energy Rev 1(38):639–650

6. Matsunaga F, Zytkowski V, Valle P, Deschamps F (2022) Optimization of energy efficiency in smart manufacturing through the application of cyber–physical systems and industry 4.0 technologies. J Energy Resour Technol 144(10):102104
7. Gong K, Yang J, Wang X, Jiang C, Xiong Z, Zhang M, Guo M, Lv R, Wang S, Zhang S (2022) Comprehensive review of modeling, structure, and integration techniques of smart buildings in the cyber-physical-social system. Front Energy 1–21
8. Shi X, Li Y, Cao Y, Tan Y (2015) Cyber-physical electrical energy systems: challenges and issues. CSEE J Power Energy Syst 1(2):36–42
9. Alajmi A, Kelly N (2024) Implementing industry 4.0 tools for enhancing residential energy management: a case study of Kuwait. In: Proceedings of 2024 IEEE 18th international conference on application of information and communication technologies (AICT), Turin, Italy, pp 1–7
10. Moreno Escobar JJ, Morales Matamoros O, Tejeida Padilla R, Lina Reyes I, Quintana EH (2021) A comprehensive review on smart grids: challenges and opportunities. Sensors 21(21):6978
11. Praveen RP, Keloth V, Abo-Khalil AG, Alghamdi AS, Eltamaly AM, Tlili I (2020) An insight to the energy policy of GCC countries to meet renewable energy targets of 2030. Energy Policy 1(147):111864
12. Muralidhara S, Hegde N (2020) An internet of things-based smart energy meter for monitoring device-level consumption of energy. Comput Electr Eng 1(87):106772
13. Alajmi AF (2021) Implementing the Integrated Design Process (IDP) to design, construct and monitor an eco-house in hot climate. Int J Sustain Eng 14(4):630–646

Open Access This chapter is licensed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.