Teaching Smart Power Grids: A Sustainability Perspective

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***Abstract*—Over the last few years, smart (power) grids course has become a part of the electrical and computer engineering curriculum. Due to the multidisciplinary nature of the smart grids, teaching methods and materials vary significantly across universities. In this paper, we present our experience in teaching smart power grids course at the division sustainable development at Hamad Bin Khalifa University. The class was offered during Fall 2016 and 2017 semesters and the class roster was composed of graduate students with diverse engineering backgrounds such as electrical, mechanical, chemical, petroleum, and materials science. Special attention has been given to smart grid applications that require end-user involvement such as distributed renewable integration, electric vehicles, and demand-side management programs.**

***Index Terms*—smart grids education, sustainability.**

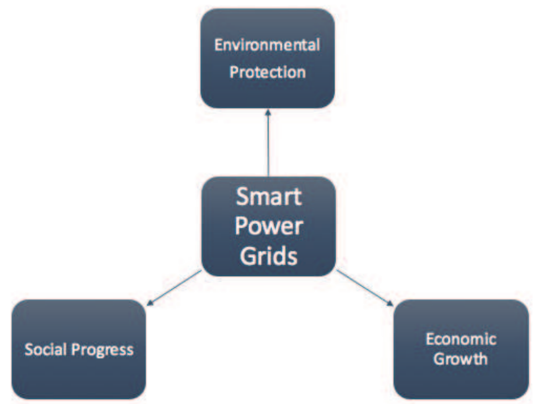

Fig. 1. Smart power grids as an enabler of sustainable development.

I. Introduction

The electricity sector is one the main drivers of social and economic development, while it is also one of the primary sources of greenhouse gas (GHG) emissions. Therefore, the role of smart grids as a provider of affordable, stable, clean, efficient, and sustainable electric power to societies is of great interest for sustainability (depicted in Figure 1). Traditionally, power grids education is primarily offered at electrical engineering departments and mainly concerned to teach *in-depth* analyses of power system operations which aim to maintain the real-time balance of supply and demand. On the other hand, this paradigm has been gradually shifting towards smart power grids which are decentralized, resilient, more efficient, greener, and customer-responsive power grids that could also electrify transportation via plug-in electric vehicles (PEVs). To realize this shift, smart grids will utilize advanced information and communication technologies (ICT), a variety of monitoring and measurement devices (i.e., smart meters, phasor measurement units, etc.), high-efficient smart power electronics, renewable energy technologies, and energy storage systems (ESS) [1]. When integrated with ICT networks, power grids inherently become cyber-physical systems which could be vulnerable to cyber-attacks. Moreover, when aggregated, the engagement of end-users as distributed producers, along with their storage capabilities either via PEVs or ESS, make them a natural player in market operations. It is clear that the interdisciplinary expertise is required to teach breadth and broad coverage of smart grids education.

In this paper, we present our experience in teaching smart grids course for graduate students at the Division of Sustainability at Hamad Bin Khalifa University. One of the main goals of this course is to shine the light in the increasingly critical complex nature of the electric power grids. Famous *elephant and the blind men* parable is often used to describe the priorities, perspectives, and understanding of the power grids and the projected changes with smart grids. For instance, power engineers are primarily interested in matching supply with demand, preserving power quality, and protecting grid assets, while power electronics experts focus on novel devices and techniques to for AC/DC conversion and PEV charging. Mechanical engineers are interested in controlling HVAC systems during demand-response events and improving their overall efficiency. Similarly, material scientist and chemists focus on developing higher efficiency photovoltaics and energy storage systems for renewables. Last but not least, policy-makers are interested in reduced greenhouse emissions and improved energy security. Therefore, this course aims to shed light on different aspects of the grids by harmonizing various visions, perspectives, and priorities in the context of sustainability. The main motivation for this approach is not

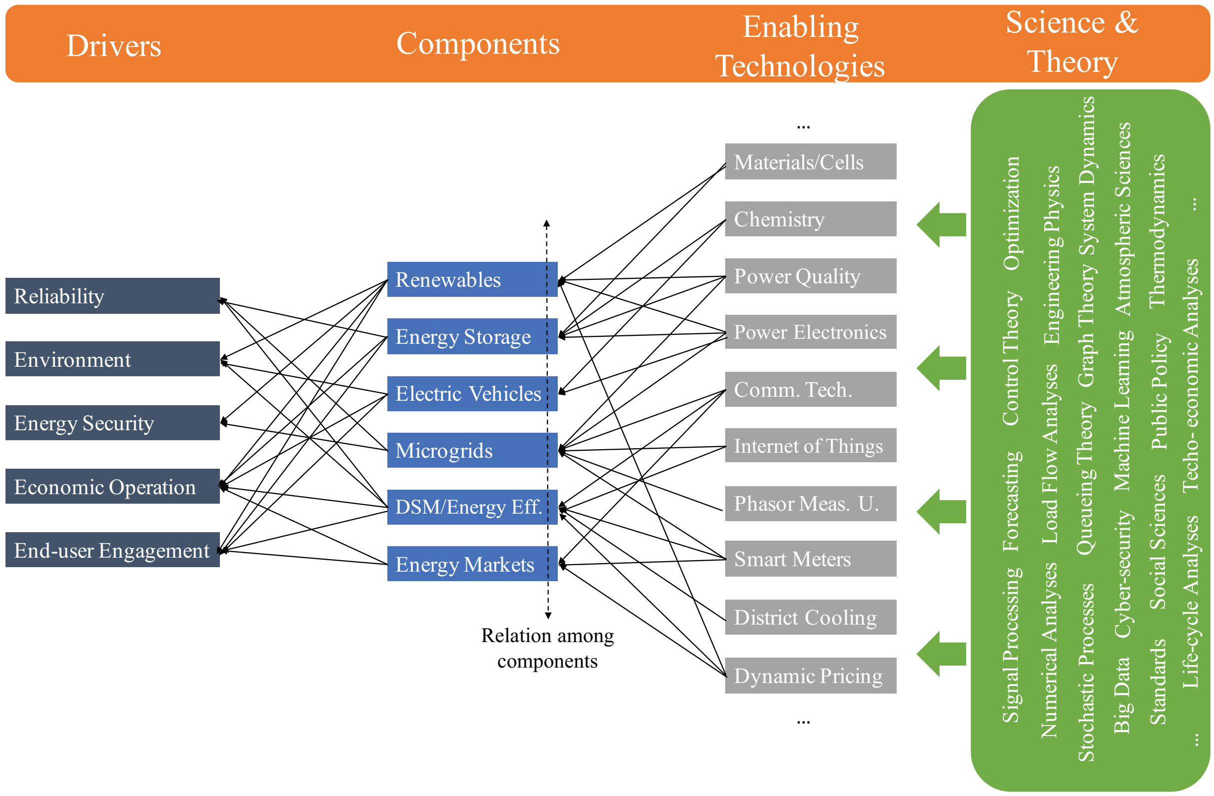

Fig. 2. An overview of related teaching materials in smart power grids course.

only to teach students from the electrical engineering background, but also to articulate the knowledge for students with various backgrounds such as chemical, mechanical, material scientist, civil, and petroleum engineering. As shown in Fig. 2, smart grids require expertise from a variety of disciplines and therefore the flavor of the course set up is to find common ground for all groups of interest.

The World Commission on Environment and Development defined sustainability as "development that meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs" [2]. As shown in Fig. 1, electricity grids lie at the heart of sustainable development as they empower social and economic progress and also have an impact on the environment. Smart power grids aim to provide reliable and secure electricity supply by enhanced monitoring and control, reduce environmental impacts by employing renewables and shaving peak consumption through demand-side management (DSM), and provide access to electricity to remote communities in underdeveloped parts of the world by microgrids. Moreover, electricity consumption and economic productivity are closely linked as electricity is crucial in energizing commercial and industrial activities. This course is particularly important for the electricity sector in Qatar because Qatar is one of the highest energy consumer (per capita basis) in the world and Qatar National Vision 2030 targets more efficient way of electricity usage and increasing the share of renewables.

The literature contains several papers that discuss experience and challenges associated with offering smart power grids course. In [3], authors present their experiences in teaching smart grid cyberinfrastructure course in their university. The course has been offered to graduate and senior undergraduate students from electrical and computer science students. The course has four main teaching topics: (1) power systems, (2) communications, (3) data management and computing, and (4) cybersecurity. In [4], teachers discuss their project-based teaching approach for sustainable energy system and smart grid. Teachers choose energy storage PV rooftop system as a case study to teach various parts of smart grid systems. Similarly, references [5] and [6] discuss smart grids course material offered in the electrical engineering curriculum.

II. Smart Power Grids Course Development

A. *Sustainability Context*

The content of smart grids course is geared towards sustainable development as electricity grids are central for economic and social progress, while electricity generation is responsible for more than one-third of the global greenhouse gas emissions. In addition world population, hence corresponding electricity consumption is growing and causing more emissions due to dominating share of fossil fuel usage. In traditional power grids planning, utilities invest in new generators, transmission lines, and distribution assets to meet the peak demand with typically diesel generators which are costly and pollutant. Therefore, developing sustainable energy generation is vital and smart grids components such as renewables, storage units, and demand-side management (DSM) support sustainable development.

"SENR 654: Smart Power Grids" course is formed in four intersecting domains. The first group is the *technology domain* which covers legacy power grid components and enabling smart grid technologies such as renewable generators, storage units, microgrids, monitoring, control, and communication systems. This part is the engineering side of the class and working principles, highlight governing equations are taught and system architectures are explained. Even though smart grids promise environmental and economic benefits, required investments are usually long-term and capital-intensive. Therefore, it is vital to assess *economic analyses* of such systems to quantify the benefits under various scenarios. With various case studies, the material includes techno-economic analysis of smart grids components such as energy storage systems, plug-in electric vehicles, and PV rooftop systems. Moreover, smart grids proactively engage end-users to adopt new technologies. Hence, it is critical to examine and analyze the *social dimension* of smart grids. The third domain contains studies from social studies, behavioral economics, and diffusion of innovations that help students to understand the long-term success of smart grids. The fourth domain is the *policy section* that is essential for the success of power grids. In the absence of supporting legislative and regulatory policies, transition towards *costly* new technologies may not be possible. The teaching approach is presented in Fig. 3. For instance, for the case of plug-in electric vehicle integration such domains are as follows [7]:

- **Technology Layer:** Energy storage systems, uni- and bi-directional chargers, electric motors, communication standards, etc.
- **Economic Layer:** (1) Economic operation of power grids such as preserving power quality, voltage imbalances, ensuring grid reliability, and deferring system upgrades. (2) Economic provisioning of resources such as optimal sizing and siting of charging stations, pricing policies, congestion control, and (3) Economic charging of vehicles and reducing battery degradation.
- **Social Layer:** Studies including behavioral economics, diffusion of innovations, and theory of planned behavior to analyze the acceptance pace of PEVs among the society.
- **Policy Layer:** Policies boosting PEV integration such as purchase rebates, tax credits, parking exemptions, emission test exemption, and HOV exemptions.

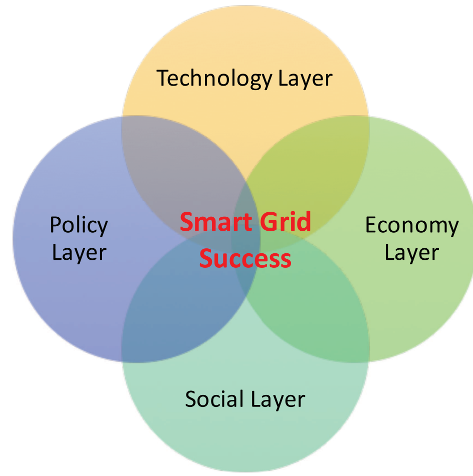

Fig. 3. Teaching approach.

B. Student Learning Outcomes

In line with the course set up, student learning objectives are determined as follows:

- Analyze the current power grid operations, identify the current issues, and understand drivers towards smart grids.
- Identify and address the benefits and issues related to renewable energy integration, demand-side management, and energy efficiency.
- Design architectures for the electric vehicle charging, PV rooftop + storage, and demand-side management technologies.
- Analyze end-user electricity consumption behavior and examine different methods to shape load profiles.
- Understand the operation principles and the role of different control, optimization, and communication technologies in developing smart energy grids.
- Conduct basic economic analysis to quantify and evaluate the smart grid benefits.
- Analyze the role of electricity in sustainable development and energy security.
- Get a structured overview of the role of enabling communication and sensing technologies for cyber-physical systems.
- Analyze social and political aspects that can boost the adoption of smart grid technologies.

C. Weekly Course Material

The course material is in parallel with the synopsis presented in Fig. 2 and contains the following weekly materials.

1) Introduction to Power Systems: A Historical Overview. Energy security and sustainable development. Energy by the numbers.
2) The business of electric Utilities: Market types, customer types, rate making.
3) Generator types, electricity markets, economic dispatch, unit commitment problems-1.
4) Generator types, electricity markets, economic dispatch, unit commitment problems-2.

Fig. 4. An overview of student project set-up.

5) Power quality, distribution network design. Transmission networks and congestion.
6) End-user Load Types. Load monitoring techniques. Load flexibility. Student presentations.
7) In-class midterm-1.
8) Microgrids: Modeling, protection, and control. Off-grid and on-grid microgrids.
9) Electrification of transportation: Motivation, definitions, economic analysis. Barriers to mainstream acceptance, impacts on power grids.
10) Energy storage systems and their working principles. Cost-benefit analyses.
11) Renewable Energy Integration. PV + storage systems. Techno-economic Analyses. Rooftop Economics.
12) Demand side management for smart grids: pricing models, energy efficiency, direct-load control.
13) Social, political, and regulatory issues. Roadmap for Qatar's Smart Grid.
14) Enabling technologies: smart grid communications. Network architectures, power line communications, advanced metering infrastructure, sensor technologies. Student paper presentations.
15) Final Exam.

It is noteworthy that the first half of the class (weeks 1-6) contains conventional power grid operations, analyzes the issues, and discusses the drivers towards smart power grids as: (1) need for improved system reliability, (2) issues with environmental impacts, (3) motivation towards energy security, (4) economic operation of power grids, and (5) end-user engagement. In the second part of the class, we discuss smart grid components and enabling technologies.

D. Learning Assessment

Learning assessments activities have been designed as follows:

1) Homework Assignments: : Five to six homework assignments are given to improve quantitative problem-solving skills. Sample homework questions are as follows:

- Auction in Generation Dispatch: Given forecasted load requirement, students are asked to calculate market clearing price for (1) no transmission cost and limit, (2) with transmission cost and limit, (3) increasing load to a higher level and seeing the effect of peak consumption.
- Unit Commitment Problem: In a toy example with four generators and three-time slots, students are asked to calculate of optimal generator output at each time slots by considering generator constraints such as minimum up and down times and ramping capabilities.
- Load Factors: Calculating load factors for residential, commercial, and industrial sectors.
- Rooftop Economics: Calculating the space required to meet a residential load for various PV module costs and efficiencies.
- Techno-economic Analyses: For a given energy storage application (i.e., residential bill management), calculating the lifetime (10-15 years) cost and benefits under various financial assumptions (i.e., inflation rate, etc.).
- Electric Vehicle Charging: Calculating the cost of charging a vehicle battery (electricity paid to utility and battery degradation cost) under various pricing and charging technologies.
- GHG Emissions: Calculation of GHG emissions due to different generation mix for charging different electric vehicles.
- Direct-load Control: For a given set of measurements from direct-load control of air-conditioning (AC) units experiments, students are asked to calculate demand reduction potential for various AC cycling durations (i.e., 15 min to one hour) for a given building stock.

2) Projects: Two types of projects are also part of the learning assessment. In the first project, students are asked to measure their electricity consumption using Smappee Energy Monitors [8]. The monitors are chosen because it does not require a technician to install, measures electricity consumption via current-clamps, and uploads data to a cloud. Next, PV-output measurements from HBKU's behind the meter PV system were given to students [9]–[11] and they were asked to calculate self-sufficiency and self-consumption values for their homes. In the final stage, students were asked to assess the benefits of using a battery system. Since the class is offered during Fall semester, students further discussed possible outcomes for the summer season. An overview of the experimental set-up is presented in Fig. 4. Second project type was preparing reports on selected topics and presenting them in class. Project material is chosen from top journals such as IEEE Transactions and related Elsevier Journals. Our experience shows that students tend to choose topics related to their backgrounds.

3) Exams: One mid-term and one final exam were part of the learning assessment. Exam questions were composed

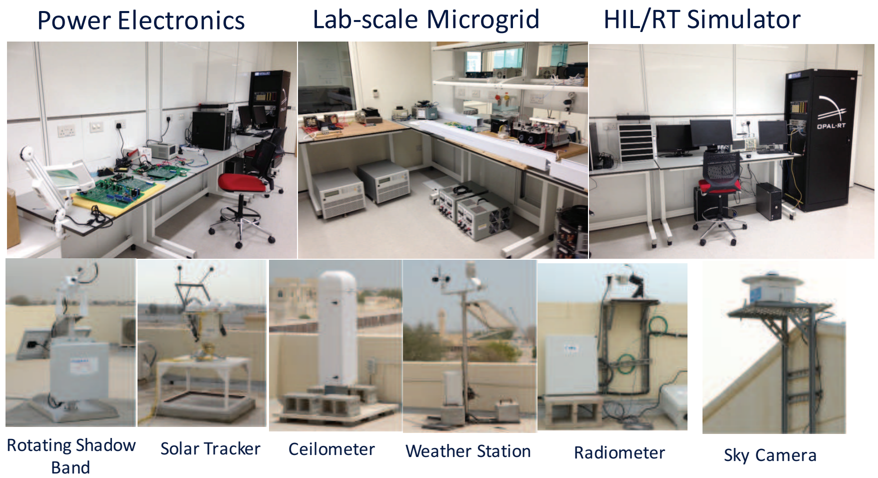

Fig. 5. An overview of smart grid lab and solar tracking equipment.

of true/false, multiple choice, short quantitative, and long quantitative questions. Open-ended questions were also asked to measure the student's depth of knowledge.

E. Smart Grids Lab

The course development is further supported by the scientist and staff of Qatar Environment and Energy Research Institute (QEERI). Currently, several scientists work at QEERI's smart grid project and the areas of expertise include microgrids, power electronics, solar systems and forecasting, and atmospheric sciences. Students were further introduced to equipments at smart grids lab (shown in Fig. 5) and several case studies were presented by the lab members. Some of the case studies include simulation with the real-time digital simulator, real-time solar energy forecasting, and real-time load monitoring from measuring devices.

F. Textbook and Resources

Even though there was no required textbook, the class material used a variety of books, journal papers, and book chapters to create the course material and teachings. These references include:

- References [12] and [13] are used in current power grid operations and basics.
- Reference [14] is used for smart grids introduction.
- References [7], [15], [16] and [14] are used from demand-side management, plug-in electric vehicles, sustainability, and microgrids.
- In addition to the books above, high-impact journals, conference papers, and technIcal reports from various organizations are used.

III. Smart Grid Challenges in Qatar

The challenges and opportunities of smart grids vary significantly across countries and within regions of a single country. Even though the course material is directed towards providing a global view, special attention is paid to address the smart grid challenges in the State of Qatar. [17]. The power grid operations in Qatar is facing new challenges and uncertainties in the near future. First, Qatar is taking bold steps to generate a sizable portion of its electricity through renewable photovoltaic (PV) systems; the targets are set as 200 MW by 2020 and 2 GW generation capacity by 2030 [18]. Higher shares of non-dispatchable energy sources, such as PV farms, are likely to have disruptive impacts on the power grids. Electricity is a unique commodity that its bulk storage is not feasible at a reasonable cost, hence, entities running the power grids need to monitor, control, and match the supply with demand at all times. On the other hand, Qatar is surrounded by deserts and surface soiling due to dust deposition create significant fluctuations in PV output. To compensate for PV intermittency, dispatchable generators may need to ramp-up and ramp-down more frequently, and this situation will inherently introduce an additional cost and uncertainty to system operations. Furthermore, for the case of PV rooftops, if the time of the PV generation and consumption do not match, PV power output injected back to the grid can cause voltage deviations and degrade power quality. Discussion on "duck curves" for Qatar and hidden costs associated with PV integration is discussed in detail.

As a second challenge, Qatar is aiming to remove the subsidies in the energy sector and plans to employ the time of use or dynamic pricing schemes to recover the cost of electricity provisioning [19]. Considering the fact that Qatar has the highest energy subsidy per capita in the world, this shift is likely to change the electricity consumption patterns and change the utilization of power system assets. Such pricing techniques are established based on consumption patterns, duration of peak hours, and the type of loads used during peak hours. Hence, it is necessary to examine the customer responses to the new pricing regimes and assess the potential applications of other demand-side management techniques such as direct load control (DLC). The last challenge is the participation to Gulf Cooperation Council (GCC) interconnection market. Recently established energy markets allow Qatar to exchange power with neighboring countries. Qatar generates all of its electricity from natural gas and can exploit unused capacity to sell power to its neighbors who significantly use petroleum as the main source of fuel for electricity. To that end, electricity consumption patterns, load factors, and PV generation patterns are discussed in detail.

IV. Conclusions

In this paper, we have presented our experience with teaching smart power grids course at the division of sustainable development. The class material is composed of technology, economy, social, and policy components. Teaching experience shows that proposed method has been successful in reaching out students from various backgrounds. Since smart grids education is in its infancy stage, we strongly believe that sharing such experience will be useful develop smart grids curriculum.

V. Acknowledgements

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