Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 176 (2020) 2254–2263

Procedia Computer Science

www.elsevier.com/locate/procedia

24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

Smart Energy and power systems modelling: an IoT and Cyber-Physical Systems perspective, in the context of Energy Informatics

Chiara Bordin[a,*], Anne Håkansson[a], Sambeet Mishra[b]

[a]*The Arctic University of Norway, Hansine Hansens vei 54, Tromsø 9019, Norway*
[b]*Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia*

Abstract

This paper aims at identifying the key role of "Smart Energy and Power Systems Modelling", within the context of Energy Informatics. The main objective is to describe how the specific subject of "Smart Energy and Power Systems Modelling" can give a key contribution within the novel domain of Energy Informatics, by successfully linking and integrating the different disciplines involved. First the paper will present how and where the specific subject of "Smart Energy and Power Systems Modelling" can position itself within the broad Energy Informatics domain. Afterwards the paper will explain how Cyber-Physical Systems (CPS) and Information and Communication Technologies (IoT), coupled with "Smart Energy and Power Systems Modelling", can enhance the Energy Informatics domain. In addition, the main challenges and opportunities for Energy Informatics specialists will be outlined, with regard to the interdisciplinary approach that characterises this field.

Keywords: Cyber Physical Energy Systems; Energy Informatics; Energy Systems; Interdisciplinary; IoT; Mathematical Modelling; Optimisation; Power Systems

1. Introduction

The Climate change, the need for decarbonisation, as well as the increasing energy demand, together with the massive penetration of renewable energy resources, are creating many challenges for the current and future energy and power systems. Such challenges cover simultaneously technical, economic, and social issues, that must be addressed holistically, in order to find comprehensive answers to the wide variety of research questions that arise within the energy and power systems field. On the technical side, network stability, system adequacy, power quality [1], monitoring

* Corresponding author: Chiara Bordin
E-mail address: chiara.bordin@uit.no

10.1016/j.procs.2020.09.275

systems, and predictive maintenance [2] are playing a vital role for the overall system operations. On the economic side, electricity markets, novel trading mechanisms between microgrids [3], technological learning curves [4] and degradation issues of the available resources (such as batteries [5]), are increasing the complexity of the investment decision making processes for the systems design and expansion. In addition, the techno-economic issues cannot disregard the social aspects and the impacts of human behaviour on the overall energy and power systems. Nudging [6], demand response [7], arbitrage [8], can all influence the behaviour and decision making of consumers towards more sustainable choices and load shifting.

In such a wide and complex context, an interdisciplinarity approach becomes vital. A conventional definition of interdisciplinarity emphasises the collaboration between several disciplines around a common research topic. Interdisciplinary energy research can simultaneously open up new avenues of research and provide answers to questions that remain open [9]. Therefore, in these days and age, interdisciplinarity is the key to properly address the many challenges that arise in the increasingly complex energy field. It is also key to properly catch the many opportunities to look at the various energy related problems from different perspectives, by using the available knowledge from different disciplines in a transversal way.

When addressing such interdisciplinarity, it is worth mentioning also that the Energy domain is experiencing a paradigmatic change by integrating conventional energy systems with advanced information and communication technologies (ICT) [10]. From this point of view, the novel domain of Energy Informatics comes into the picture as a way to involve several disciplines to address the recent energy and power systems challenges. Its goal is to use emerging new information and communication technologies to make energy systems more and more efficient, effective, safe, secure, economical, and clean.

Within the broad Energy Informatics domain, an important role is covered by ”Smart Energy and Power Systems Modelling” [11]: this refers to the process of building computer models of Energy systems, in order to analyze them. Indeed, Energy modeling has increased in importance as the need for climate change mitigation has grown in importance [12]. Models often use mathematical optimisation to minimise or maximise an objective function, by fulfilling a set of equalities and inequalities, in order to provide optimal decisions in terms of investment and/or operations.

In addition, Cyber-Physical Systems (CPS) play a key role in most of the energy related problems. Indeed, on one hand there is an increasing availability of data coming from the physical space through sensors, devices and smart meters. On the other hand, this massive data available, brings an increasing need to manipulate and utilise such data within a cyber space, in order to support and enhance the various decision making processes and systems operations. From this point of view, smart grids in particular integrate the physical systems (power network infra-structure) and cyber systems (sensors, ICT, and advanced technologies), and exhibit characteristics typical of CPS [13].

On top of that, Internet of Things (IoT) is considered the expansion of the Internet services due to the proliferation of sensors, smart devices, and “things” on the Internet [14]. Effective functioning of the smart grids can be achieved by using the IoT computing paradigms as a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols [13].

The first objective of this paper is to identify the key role of ”Smart Energy and Power Systems Modelling”, within the broad context of the Energy Informatics. The reason for choosing such focus, is that modelling is already involved in a number of Energy Informatics areas, and it has the potential to be involved in many of those areas that are not (yet) linked to it. Indeed the versatility and interdisciplinary properties of modelling, have not yet been fully explored, discussed, and exploited within the Energy Informatics domain. Modelling represents therefore an area that is worthy to further discuss, in the broader context of Energy Informatics. Through this paper, the authors are willing to shed light on how the specific subject of ”Smart Energy and Power Systems Modelling” can give a key contribution within the broad domain of Energy Informatics, by successfully linking and integrating the different disciplines involved. The second objective is to identify how CPS and IoT, coupled with ”Smart Energy and Power systems Modelling”, can enhance the Energy Informatics domain.

The remainder of the paper is organised as follows. Section 2 will explore the main properties of the Energy Informatics domain, in light of the most recent literature, research, and teaching activities that are performed. The Section 3 will debate how ”Smart Energy and Power Systems Modelling” can position itself within the broader domain of Energy Informatics. The following sections 4 and 5 will discuss the role of CPS and IoT respectively, and how they can be coupled with ”Smart Energy and Power Systems Modelling” to enhance the Energy Informatics domain. Based on the discussions of the previous sections, the Section 6 will propose three dimensions for the Energy Informatics domain. Section 7 will outline the main opportunities and challenges linked to the intrinsic interdisciplinarity required within the Energy Informatics domain. Finally, Section 8 will summarise the conclusions.

2. The domain of Energy Informatics

The main features of the novel "Energy Informatics" domain, can be identified in light of the recent scientific literature. The available scientific literature defines Energy Informatics as a subject where researchers aim at "exploring the intersection of informatics, power engineering and energy economics" [15]. Authors in [16] discuss the scope of Energy Informatics, by identifying two main goals of energy efficiency, and renewable energy supply. According to the authors, these goals drive the development of smart energy-saving systems and smart grids respectively. The Springer Journal "Energy Informatics" [17] defines this domain as "the application of digital technology and information management theory and practice, to facilitate the global transition towards sustainable and resilient energy systems". Professor Frank Eliassen, in one of his guest lectures at the Arctic University of Norway [18], defined Energy Informatics as *"an emerging interdisciplinary domain that lies at the intersection of energy systems, power systems, economics, computer engineering, and computer science. Energy Informatics studies information and communication technology means to more effectively manage energy resources, fossil resources as well as renewable resources."*.

The scientific literature provides a view on Energy Informatics that includes topics such as smart (power) grids, smart meters, demand response, smart buildings, electric mobility, energy storage, data centres, energy policy, energy markets and market mechanisms, etc.

However, given that Energy Informatics is a very young and dynamic research area, it is also important that researchers can participate in the field by bringing works where their own imprint can also be visible, in order to provide an additional contribution within the common frame and background. This means that it is also important that different researchers' contributions, will have some distinguishing features, even though they will lie on a common ground and foundation. The identification of such common grounds and foundation, as well as the inclusion of own distinguishing features, should never disregard the obvious fact that the subject "Energy Informatics" is basically made of two very well defined and self contained words: Energy and Informatics. Therefore, it is by touching and linking both topics – Energy and Informatics – that we can reach the goal of a successful, meaningful and comprehensive development of the "Energy Informatics" domain.

The Energy topic is very broad, however, to have a better understanding of what fits within this topic, it is possible to look into the subject classification of the Journal of Energy (ISSN: 0360-5442), by Elsevier, which is a very established and high ranked journal (Cite Score 6.20, IF 5.537). The mentioned subjects [19] are the following: heat transfer, energy conversion and efficiency, district heating and cooling, energy in buildings, solar thermal, geothermal and organic rankine cycle, thermodynamics, fossil fuels, biofuels, hydrogen, energy carrier, storage, electricity demand, smart grid, smart energy systems, wind power, renewable energy, energy and transportation, integrated heating, cooling and electricity, national energy systems, energy and environment, energy planning, energy policy, energy economics, carbon capture, nuclear.

The Informatics topic is very broad as well, and it can be easily identified by looking into the fundamental subjects that are generally taught within traditional Computer Science study programmes. What we normally find within such study programmes are the following fundamental disciplines: distributed systems, parallel programming, advanced database, programming, computers communication, computer security, software engineering, green computing, artificial intelligence, operating systems, algorithms.

It is worthy to mention that Energy Informatics is defined as a strongly interdisciplinary subject, which means that a versatile and interdisciplinary approach that brings together relevant different subjects to solve energy related problems, is a successful one.

3. The key role of mathematical optimisation in the context of Energy Informatics

As discussed in the previous section, the key contribution of Energy Informatics is to build links and connections between the subjects listed in the previous section. From this point of view, mathematical modelling and optimisation offers a very interdisciplinary, versatile and powerful tool to study smart energy and power systems from a socio-techno-economic perspective, by creating links between the key subjects of Energy and Informatics. Indeed, optimisation models can be used to analyse optimal investment decision making in energy resources, as well as optimal operational management of energy and power systems [20]. This can be done at different levels of details: for example, starting from the broad high level models of the whole European Energy system [21], it is possible to move towards local models for smart microgrids design [22] or thermal networks design [23], and then move further into the more detailed optimal power flow models for network restructuring and reconfiguration [24]. It is then possible to increase the level of details by looking into more detailed models for smaller systems like charging sites [25] or buildings [26], and further move down towards the detailed and specific models of single generator units [27] or specific storage technologies [28]. There is potentially no limit to what can be modelled and investigated with such tools, both on the thermal energy side and on the electrical side, with possibilities to potentially touch all the topics listed in the Energy Journal subject classification, as long as the technical competences of the specific subjects are available.

Therefore, the discipline of ”Smart Energy and Power Systems Modelling”, plays a key role to holistically cover the Energy Informatics domain, through the use of mathematical optimisation as a background.

In particular, energy systems optimisation focuses on the generation of electricity (various forms of energy resources optimization, renewable and non renewable). While power systems optimisation focuses on the overall power system, from generation of electricity to the transmission and distribution. It would therefore study the basics to optimally transmit, distribute, operate, maintain and protect the entire system. The Figure 1 shows how the core subject of “Smart Energy and Power Systems Modelling” can be linked with the fundamental subject of Computer Science in particular and with other key fundamental subjects in general, to fulfill the interdisciplinary broad scope of Energy Informatics.

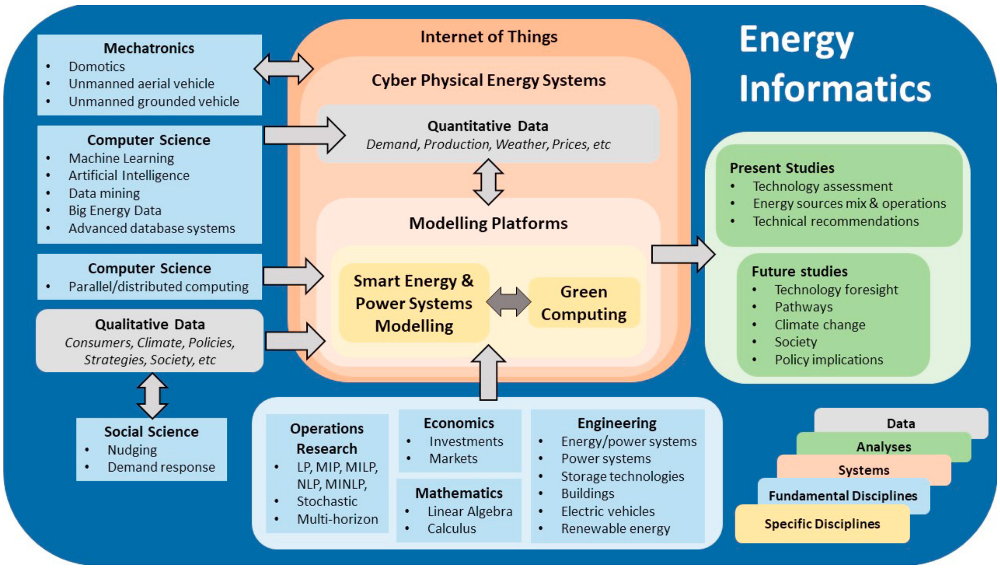

Fig. 1. Overview of the Energy Informatics main elements and key links between them

As shown in the yellow part of Figure 1, together with “Green Computing”, the ”Smart Energy and Power Systems Modelling” subject would lie at the heart of the Energy Informatics domain. These are two distinct and self-contained subjects, but with also many links that can potentially be explored. “Green computing” [29] aims at investigating means to make computing as a whole more sustainable, including means to save energy in software and hardware systems. It is therefore a subtopic of Energy Informatics with a very specific focus on improving the efficiency and consumption of computing systems. The “Smart Energy and Power Systems Modelling” is focusing on the optimal design, expansion, management and operation of energy and power systems, by including key elements such as renewable sources, storage technologies, electric vehicles, smart grids, smart buildings, as well as social aspects such as nudging and demand response. It is therefore a key subject to provide a holistic understanding of the Energy and power systems issues. The “Smart Energy and Power Systems Modelling” can bring “Green computing” into a broader perspective by including the computers sustainability issues within the power and energy systems optimal design and operations. On one hand, the "Green computing" can add key specific elements to the "Smart Energy and Power Systems Optimisation" tasks. And on the other hand, the "Smart Energy and Power Systems Optimisation" can provide a more holistic perspective to study the specific issues that arise in Green Computing. Therefore, even though they represent very well defined and self-contained subjects, still connections between them arise as outlined above, which explain the reason for the double arrows in Figure 1.

Through the "Smart Energy and Power Systems Optimisation" subject, connections with other fundamental subjects arise straightforward, due to the intrinsic interdisciplinarity that characterizes the mathematical modelling field. In order to apply mathematical optimisation to energy and power related problems, it is necessary to utilize a holistic socio-techno-economic approach that combines knowledge of engineering, mathematics, economics, social science and operations research. Figure 1 shows a list of relevant subtopics for such disciplines. Several computer science subjects have also links with the "Smart Energy and Power Systems Modelling" subject. Indeed, modelling requires programming skills to develop the models prototypes. Python has become the most popular programming language in energy systems modeling [30], through the Pyomo package [31]. Moreover, different models built at different levels, can be linked and integrated within modelling platforms [32]. Here cluster computing, together with parallel and distributed computing, can enhance the computational requirements needed to solve bigger real world instances. They can also provide powerful means to solve more complex problems that arise with the novel peer to peer communication and trading mechanisms between microgrids [33], [34]. Modelling requires also data gathering, management and manipulation, in order to generate long and short term scenarios and projections of generation, demand, prices, costs, weather etc. Again computer science can enhance the quality of energy and power systems models by providing better dataset and forecast through machine learning, big data, data mining and artificial intelligence. Moreover, database systems come into the picture for data management and data visualization within the broader decision support tools that can be developed through mathematical optimisation. It is worth mentioning that data have to be provided both at a qualitative level and at a quantitative level. Quantitative data can be gathered through sensors, smart meters, intelligent devices (i.e. sensors, thermostats), grid equipment, Geographic Information Systems (GIS). However, the quantitative properties of the Energy and power systems, cannot disregard the social aspects and the impact of human behaviour on the grid. Qualitative data like customers behaviour are less structured than quantitative data. They are strongly connected to social science disciplines, where nudging [6] and demand response [35] play an important role to influence the behaviour and decision making of consumers towards more sustainable choices and load shifting. In addition, future long term projections (several decades) of demand trends, climate change, technological improvement, societal and political development, have to be generated at a qualitative level. This is generally done by combining contributions from expert opinions, information contained in reports provided by established energy agencies, as well as information about societal development and policy actions [25].

As shown in Figure 1, CPS and IoT represent the systems interface through which the key links between fundamental disciplines, specific disciplines, qualitative data and quantitative data, are established, in order to lead towards the possibility of running a wide variety of energy and power systems analyses. The CPS and IoT role will be further discussed in the following sections 4 and 5.

The overall setting presented in Figure 1, allows performing much more comprehensive and complex analyses, that would not be possible without the interdisciplinary approach outlined above. The authors classify these analyses in two main groups: present studies and future studies.

Present studies refer to those analyses that aim at studying the current systems as they are here and now. This can relate (but is not limited) to for instance: assessing the value of existing technologies under different specific scenarios, locations, or requirements; analysing how the integration of different technologies can improve the performance of the system; defining optimal investments in energy resources; define optimal operational management for specific systems or subsystems (ranging from optimal operations of single generator units such as combined heat and power plants, to optimal operations of energy use in buildings, to the simultaneous optimal operations of different elements within a smart grid as a whole); define technical recommendations for specific issues that arise within the smart grids (i.e. reliability issues, network restructuring, power quality etc).

Future studies refer to those analyses that aim at studying how the system should behave in the future, how the system should change in order to reach specific goals, and how future projections of technological improvement, demand, energy prices, costs, climate change, will affect both the decision making process and the way future investments will be timed throughout the years. Future studies will therefore focus on long term scenario development to foresee how different technologies will develop, define recommendations for future pathways (i.e. pathways towards low carbon energy systems), investigate the long term effects of climate change and society on the decision making process within energy systems, understand the policy implications that lay behind such decisions.

4. The role of Cyber-Physical Systems (CPS) as a key link between Energy and Informatics

CPS [36] are systems that interconnect physical parts with software to perform tasks that require a mix of cyber and physical components. These CPS range from small-scale systems like pacemaker to large-scale systems, such as power-grids. In the CPS, there are three basic technologies: embedded computing systems, networking ICT, sensing and actuating technologies. With these technologies, it is possible to provide services such as control, information feedback and real-time monitoring.

In energy systems, CPS integrate energy processes with network communication and embedded real-time system components. In energy, the CPS are good for energy efficiency, energy resource management and energy monitoring and control, thus making the systems "Cyber-Physical Energy Systems" (CPES) [37]. In the area of smart grids, the systems can control grid energy generation, load mass and distribution assets.

Distributed generated energy with smart grids can support energy systems [38]. With the technologies of CPS, adaptive performance is possible by monitoring, communicating and controlling the included parts [39], [40]. The adaptive performances entail dynamic responses and require an understanding and handling of the constraints of communication and computing. The involved parts are heterogeneous and energy sources are diverse, which challenges the performance.

As shown in Figure 1, a cyber space and a physical space are identified within the CPES. The computer models of Energy and power systems, are developed within the cyber space. As discussed in the previous sections, such models can include the more specific issues of green computing as part of the broader picture. Within the cyber space, the models are uploaded into modelling platforms and their performance is enhanced through the use of computer science techniques such as parallel and distributed computing. The models are meant to describe the real world Energy and power systems main technical properties, thus, they are strictly connected with the physical space of the CPES. The physical space is represented by the quantitative data of the actual energy and power systems, which have to be modelled at different levels, using the fundamental knowledge of engineering, mathematics, economics, and operations research disciplines. The CPES is both using and generating quantitative data through sensors, smart meters, smart devices. This explains the double arrows that is connecting the quantitative data from the physical space, with the computer models embedded in the cyber space. Qualitative data, as outlined in the previous section, are not directly generated by CPES, and they are therefore appearing outside the CEPS box in Figure 1. They are anyway sent directly into the modelling platform, to be manipulated and utilised as input within the smart energy and power systems optimisation models.

Models are built such that they can combine the data from computational elements and physical elements, to improve performances making efficient and effective energy systems. The models can optimize the energy systems by improving the power consumption based on time, changes in climate, and energy sources etc. By using the physical space information coming from sensors, smart meters and smart devices, it is possible to investigate energy and power systems at different levels. For instance, it is possible to study optimal energy management in buildings, hydropower operations, predictive maintenance of the power grid, grid connected or offgrid systems real time operations etc.

Therefore, the CPES represent the key interface between the real world energy and power systems, and its theoretical representation within abstract mathematical optimisation models.

Every CPS that is connected to the internet can become an IoT.

5. The role of IoT to enhance energy systems management and analyses

The advancements in the information and communication technologies has paved the way for a tightly interconnected world (seamless interactions and access to communication devices such as phones). The IoT connects machines to each other such that systems can operate without human interactions [41, 42, 43]. Consequently, IoT enables controlling equipment at home and power generation plants through internet. Mechatronics is a branch of science that combines both mechanical and electronics components. Mechatronics devices and components are becoming increasingly integrated with and within the wider systems concepts of CPS and IoT [44]. IoT is therefore strongly interconnected to the mechatronics domain. For example, a washing machine is a mechatronics system, composed of sensors, actuators, microprocessors and mechanical parts. Through mobile applications via internet, such systems can be remotely controlled and therefore they create an IoT system.

Energy management in buildings is advancing towards smart homes, also known as home automation or domotics [45]. As an application of Mechatronics, the domotics refers to systems through which it is possible to control lighting, climate, appliances, as well as security and entertainment systems within the house. When connected with the Internet, home devices become an important constituent of the IoT.

The smart grid is also advancing towards automation, including automated decision making and control. Unmanned Aerial Vehicles (UAV) and Unmanned Grounded Vehicles (UGV) are considered as part of the mechatronics. UAV and UGV are essentially CPS, but with internet connection they become IoT, and they can be used on ground to bring further automation into the existing power system. They can for instance be utilised for diagnosing and localizing of the faults in the power system. Some examples aimed at including IoT systems and mechatornics within the smart grids automations, are available in literature. An IoT based maximum power point tracking have been investigated for a solar power plant in [46]. Fault diagnosis for power transmission lines have been investigated by the authors in [47]. An IoT concept for small virtual power plant in arduino platform is presented in [48]. The relationship between IoT and economics of microgrid is further discussed in [49], by investigating multiple virtual power networks interactions, with high or medium voltage electricity networks. Moreover, price based demand response through smart algorithms such as ramping behaviour analysis [50] can be further integrated to the system control.

In Figure 1 mechatronics is added as a bi-directional communication layer to the top-left corner, interacting with the CPES. Mechatronics establishes a bi-directional communication to receive information and send control signals for a real-time control.

On top of CPS, the IoT enhances the interfaces to gather the data from different physical sources, so that they can be manipulated and utilised within the cyber space. In contrast with CPS, IoT is connected to internet and therefore the network is expanded. IoT enables wireless, non-physical control for the system. Essentially every CPS can become an IoT through the connection to the internet. Thanks to IoT, the power demand can been further tuned to the consumer's lifestyle, through the utilisation of smart lights, fans, heaters and power sockets. These components can be controlled according to the user profile based on day, time, weather etc. The control can be executed through applications installed in phones or computers over internet. This motivates in turn demand side participation within the power system.

From a power systems perspective, IoT enables seamless control from consumer's device over the internet to control the grid equipment. For example, through IoT it is possible to send price signals to the final consumers in order to affect their energy behaviours. Indeed, by reacting to the market prices, the consumers can respond through demand shifting and therefore affect the power consumption.

6. The Energy Informatics dimensions

By including IoT on top of CPES and mathematical models for energy/power systems, it is possible to identify three main dimensions of the Energy Informatics domain. The authors propose to visualize such dimensions through the "Energy Informatics cube", as shown in Figure 2. As illustrated in the Figure, CPES act as a system-wide control, meaning that CPES cover the wide variety of energy and power physical systems that can be controlled through a cyber space (i.e. the figure shows CPES examples such as a house, a washing machine, a roomba, a drone, a hydropower plant). CPES represent therefore the "width" of the Energy Informatics domain. As previously discussed, the real world energy and power systems are described within the cyber space through the use of abstract mathematical optimisation models. The models are different in size. Indeed, different models describe the systems at different depth of details. Models represent therfore the "depth" of the Energy Informatics domain. Finally, IoT adds an additional dimension on top of the other two and it expands the possibilities of control, thanks to the internet connection (the figure shows for example a computer, a tablet, a mobile phone, a smart tv, an air sensor). Indeed, the energy devices alone can be modelled and controlled as CPES to affect the physical systems, but with IoT on top, they can be managed remotely through internet for instance using mobile applications. The IoT represents therefore the "height" of the Energy Informatics domain, and it leads the systems control into the cloud computing.

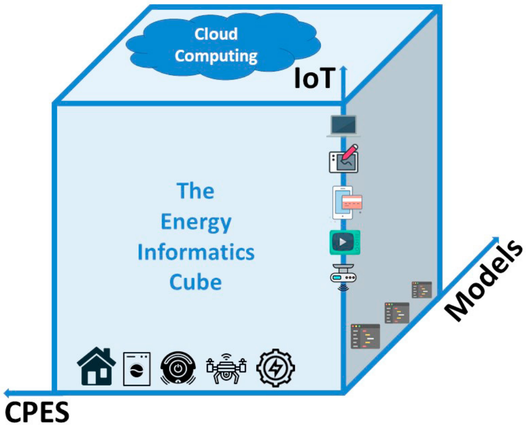

Fig. 2. The ”Energy Informatics Cube” representing the three main Energy Informatics dimensions

7. Opportunities and challenges for Energy Informatics specialists

As outlined in the previous sections, the interdisciplinary approach that distinguishes the Energy Informatics domain, is key to enhance analyses that would not be possible without the linking of different disciplines and the integration within CPS and IoT on top. Such an interdisciplinary approach is also a key aspect of the ”Smart Energy and Power Systems Modelling” discipline, which has an intrinsic versatility, as discussed in the previous sections.

However, it is worth mentioning that there is a trade off between the versatility required by an interdisciplinary domain like Energy Informatics, and the specialisation that one might gain by keeping focused on just one single subject. Indeed, versatility in itself represents both an opportunity and a challenge, not only in the research environment, but also in the industrial world. Being an Energy Informatics specialist, means having the ability to address different subjects together. However, the higher level focus required in this approach, will prevent the single specialist from deeply addressing all the knowledge that is included in all the subjects involved. An Energy Informatics specialist is required to be versatile enough and have a broad higher level understanding of many disciplines, in order to address the intrinsic interdisciplinary needs of this domain. This versatility is an opportunity, because it facilitates cooperation with peers, it creates links between different subject groups, it can open doors and build new bridges between specialists, that did not exist before. However, the risk is to end up working at the intersection of many disciplines, without actually specialising in any of them. This is the challenge that Energy Informatics specialists should constantly take care of: keep the specialisation within one core area of expertise, while being open to constantly gain new skills, and acquire broader knowledge within complementary relevant subjects.

Given that nobody can be an expert in everything, it is straightforward that team work is mandatory within the Energy Informatics domain: successful Energy Informatics specialists will be those open minded leaders with the ability to communicate with different people with different backgrounds, manage different competences at different levels, and constantly learning new skills to keep themselves at the forefront of research.

8. Conclusions and future work

The proposed paper gives a broad and complete picture of the Energy Informatics domain. It provides information on how such a novel multidisciplinary domain should be addressed, by properly linking different disciplines both on the Energy side and on the Informatics side, through the use of mathematical optimisation as a background.

The role of ”Smart Energy and Power Systems Modelling” within the broader Energy Informatics domain, is identified, by illustrating the main links between fundamental subjects, specific disciplines, qualitative and quantitative data, CPS and IoT, in order to perform specific analyses for the current and future Energy and power sytems.

The conclusion is that mathematical optimisation in general - and ”Smart Energy and Power Systems Modelling” in particular - plays a key role at the heart of the Energy Informatics domain. Indeed, it allows the creation of natural links between different subjects, in line with the intrinsic interdisciplinarity that characterizes the Energy Informatics domain. Moreover, CPS and IoT, on top of ”Smart Energy and Power Systems Modelling”, can enhance the Energy Informatics domain. In particular, CPES are identified as a key interface between the quantitative data available from the physical space represented by the real world Energy and power systems, and the abstract computational representation of such systems within the mathematical optimisation models. On top of CPES, the IoT provides connection to the internet, therefore it is identified as a system to expand communication, and realise full automated and coordinated control, which is relevant for real time optimisation. In this context, mechatronix is also identified as a key subject to receive information and send control signals through the IoT interface.

Future work will be carried out by further investigating research and innovation opportunities in Energy Informatics, with regard to the links between the specific subjects of ”Green Computing” and ”Smart Energy and Power Systems Modelling”. In addition, future work will be carried out in order to propose a proper vision for Energy Informatics accademic courses, in light of the key subjects and connections that are identified in this paper.

So far, most of the research within Energy Informatics, has been focused on the different areas, which has been treated more as self-contained topics, rather than interconnected ones. The scientific community willing to contribute to the Energy Informatics field, should focus more on research that creates links between the areas, and in particular between the three main dimensions of Energy Informatics (CPES, IoT, Models), visualized in the so-called ”Energy Informatics Cube” that has been proposed in this paper.

Acknowledgements

This paper is partly supported by the Estonian Research Council grant PUTJD915. Small icons used inside Figure 2 are procured from *freeicons.io* and *flaticon.com*.

References

[1] T. Ayodele, A. Jimoh, J. Munda, J. Agee, Challenges of grid integration of wind power on power system grid integrity: A review, world 3 (2020).
[2] T. M. Welte, J. Foros, M. Nielsen, M. Adsten, Monitorx–experience from a norwegian-swedish research project on industry 4.0 and digitalization applied to fault detection and maintenance of hydropower plants, Hydro 2018-Progress through partnership, Gdansk, Poland, 15-17 October 2018 (2018).
[3] J. An, M. Lee, S. Yeom, T. Hong, Determining the peer-to-peer electricity trading price and strategy for energy prosumers and consumers within a microgrid, Applied Energy 261 (2020) 114335.
[4] K. Handayani, Y. Krozer, T. Filatova, From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning, Energy policy 127 (2019) 134–146.
[5] C. Bordin, H. O. Anuta, A. Crossland, I. L. Gutierrez, C. J. Dent, D. Vigo, A linear programming approach for battery degradation analysis and optimization in offgrid power systems with solar energy integration, Renewable Energy 101 (2017) 417–430.
[6] R. Karlsen, A. Andersen, Recommendations with a nudge, Technologies 7 (2) (2019) 45.
[7] N. A. Mohammed, M. H. Albadi, Impact of demand response on short-term generation planning, in: 2018 IEEE International Conference on Smart Energy Grid Engineering (SEGE), IEEE, 2018, pp. 176–180.
[8] H. Nezamabadi, M. S. Nazar, Arbitrage strategy of virtual power plants in energy, spinning reserve and reactive power markets, IET Generation, Transmission & Distribution 10 (3) (2016) 750–763.
[9] M. Pellegrino, M. Musy, Seven questions around interdisciplinarity in energy research, Energy research & social science 32 (2017) 1–12.
[10] B. Huang, X. Bai, Z. Zhou, Q. Cui, D. Zhu, R. Hu, Energy informatics: Fundamentals and standardization, ICT Express 3 (2) (2017) 76–80.
[11] P. Mancarella, G. Andersson, J. Peças-Lopes, K. R. Bell, Modelling of integrated multi-energy systems: Drivers, requirements, and opportunities, in: 2016 Power Systems Computation Conference (PSCC), IEEE, 2016, pp. 1–22.
[12] M. Labriet, G. Giannakidis, K. Karlsson, B. Ó. Gallachóir, Introduction: Energy systems modelling for a sustainable world, in: Limiting Global Warming to Well Below 2 C: Energy System Modelling and Policy Development, Springer, 2018, pp. 1–13.
[13] X. Yu, Y. Xue, Smart grids: A cyber–physical systems perspective, Proceedings of the IEEE 104 (5) (2016) 1058–1070.
[14] D. Singh, G. Tripathi, A, jara,“a survey of internet-of-things: Future vision, architecture, challenges and services,”, in: Proceedings of the World forum on nternet of things (WF-IoT), 2017, pp. 57–62.
[15] S. Lehnhoff, A. Nieße, Recent trends in energy informatics research, it-Information Technology 59 (1) (2017) 1–3.
[16] C. Goebel, H.-A. Jacobsen, V. del Razo, C. Doblander, J. Rivera, J. Ilg, C. Flath, H. Schmeck, C. Weinhardt, D. Pathmaperuma, et al., Energy informatics, Business & Information Systems Engineering 6 (1) (2014) 25–31.

[17] Springer, Aims and scope of energy informatics journal, https://energyinformatics.springeropen.com, online; accessed 2020.
[18] F. Eliassen, Guest lecture: "energy informatics: Enabling sustainable energy use", https://en.uit.no/nyheter/artikkel?p_document_id=573040, online; accessed 2020.
[19] Elsevier, Subjects classification for energy, https://www.journals.elsevier.com/energy, online; accessed 2020.
[20] W. L. Theo, J. S. Lim, W. S. Ho, H. Hashim, C. T. Lee, Review of distributed generation (dg) system planning and optimisation techniques: Comparison of numerical and mathematical modelling methods, Renewable and Sustainable Energy Reviews 67 (2017) 531–573.
[21] J. van Schijndel, K. Griffioen, L. Ikele, A. ten Cate, Energy system modelling in support of the energy transition, in: Computer Aided Chemical Engineering, Vol. 46, Elsevier, 2019, pp. 103–108.
[22] S. Mishra, C. Bordin, A. Tomasgard, I. Palu, A multi-agent system approach for optimal microgrid expansion planning under uncertainty, International Journal of Electrical Power & Energy Systems 109 (2019) 696–709.
[23] C. Bordin, A. Gordini, D. Vigo, An optimization approach for district heating strategic network design, European Journal of Operational Research 252 (1) (2016) 296–307.
[24] S. Mishra, C. Bordin, I. Palu, Rnr: Reliability oriented network restructuring, in: 2018 IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University-RTUCON, IEEE, 2019.
[25] C. Bordin, A. Tomasgard, Smacs model, a stochastic multihorizon approach for charging sites management, operations, design, and expansion under limited capacity conditions, Journal of Energy Storage 26 (2019) 100824.
[26] A. Ogunjuyigbe, T. Ayodele, O. Oladimeji, Management of loads in residential buildings installed with pv system under intermittent solar irradiation using mixed integer linear programming, Energy and buildings 130 (2016) 253–271.
[27] C. Bordin, O. Mo, Including power management strategies and load profiles in the mathematical optimization of energy storage sizing for fuel consumption reduction in maritime vessels, Journal of Energy Storage 23 (2019) 425–441.
[28] A. A. Ibrahim, B. Kazemtabrizi, C. Bordin, C. J. Dent, J. D. McTigue, A. J. White, Pumped thermal electricity storage for active distribution network applications, in: 2017 IEEE Manchester PowerTech, IEEE, 2017, pp. 1–6.
[29] B. Saha, Green computing: Current research trends, International Journal of Computer Sciences and Engineering 6 (3) (2018) 467–469.
[30] P. Lopion, P. Markewitz, M. Robinius, D. Stolten, A review of current challenges and trends in energy systems modeling, Renewable and sustainable energy reviews 96 (2018) 156–166.
[31] W. E. Hart, C. D. Laird, J.-P. Watson, D. L. Woodruff, G. A. Hackebeil, B. L. Nicholson, J. D. Siirola, Pyomo-optimization modeling in python, Vol. 67, Springer, 2017.
[32] B. Müller, F. Gardumi, L. Hülk, Comprehensive representation of models for energy system analyses: Insights from the energy modelling platform for europe (emp-e) 2017, Energy strategy reviews 21 (2018) 82–87.
[33] B. Cornélusse, I. Savelli, S. Paoletti, A. Giannitrapani, A. Vicino, A community microgrid architecture with an internal local market, Applied Energy 242 (2019) 547–560.
[34] T. Morstyn, N. Farrell, S. J. Darby, M. D. McCulloch, Using peer-to-peer energy-trading platforms to incentivize prosumers to form federated power plants, Nature Energy 3 (2) (2018) 94–101.
[35] N. Good, E. A. M. Ceseña, C. Heltorp, P. Mancarella, A transactive energy modelling and assessment framework for demand response business cases in smart distributed multi-energy systems, Energy 184 (2019) 165–179.
[36] R. L. Hartung, A. Hakansson, E. Moradian, A prescription for cyber physical systems, Procedia Computer Science 60 (2015) 1552–1558.
[37] C. A. Macana, N. Quijano, E. Mojica-Nava, A survey on cyber physical energy systems and their applications on smart grids, in: 2011 IEEE PES conference on innovative smart grid technologies Latin America (ISGT LA), IEEE, 2011, pp. 1–7.
[38] S. K. Khaitan, J. D. McCalley, Cyber physical system approach for design of power grids: A survey, in: 2013 IEEE Power & Energy Society General Meeting, IEEE, 2013, pp. 1–5.
[39] M. Persson, A. Hakansson, A communication protocol for different communication technologies in cyber-physical systems, Procedia Computer Science 60 (2015) 1697–1706.
[40] A. Hakansson, R. Hartung, An infrastructure for individualised and intelligent decision-making and negotiation in cyber-physical systems, Procedia Computer Science 35 (2014) 822–831.
[41] K. Thramboulidis, F. Christoulakis, Uml4iot—a uml-based approach to exploit iot in cyber-physical manufacturing systems, Computers in Industry 82 (2016) 259–272.
[42] J. Liu, X. Li, X. Chen, Y. Zhen, L. Zeng, Applications of internet of things on smart grid in china, in: 13th International Conference on Advanced Communication Technology (ICACT2011), IEEE, 2011, pp. 13–17.
[43] D. Han, J. Zhang, Y. Zhang, W. Gu, Convergence of sensor networks/internet of things and power grid information network at aggregation layer, in: 2010 International Conference on Power System Technology, IEEE, 2010, pp. 1–6.
[44] S. Watt, C. Milne, D. Bradley, D. Russell, P. Hehenberger, J. Azorin-Lopez, Privacy matters–issues within mechatronics, IFAC-PapersOnLine 49 (21) (2016) 423–430.
[45] M. Manganelli, Z. Leonowicz, L. Martirano, Domotics: 1. introduction, in: Power Engineering, CRC Press, 2018, pp. 370–390.
[46] Y. Wang, Y. Liu, C. Wang, Z. Li, X. Sheng, H. G. Lee, N. Chang, H. Yang, Storage-less and converter-less photovoltaic energy harvesting with maximum power point tracking for internet of things, IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems 35 (2) (2015) 173–186.
[47] S. Suresh, R. Nagarajan, L. Sakthivel, V. Logesh, C. Mohandass, G. Tamilselvan, Transmission line fault monitoring and identification system by using internet of things, International Journal of Advanced Engineering Research and Science 4 (4) (2017).
[48] D. Zubov, An iot concept of the small virtual power plant based on arduino platform and mqtt protocol (2016).
[49] G. Knieps, Internet of things and the economics of microgrids, in: Innovation and Disruption at the Grid's Edge, Elsevier, 2017, pp. 241–258.
[50] S. Mishra, M. Leinakse, I. Palu, Wind power variation identification using ramping behavior analysis, Energy Procedia 141 (2017) 565–571.