Marija ILIĆ[*]

DIGITISATION AND DISTRIBUTED AUTONOMY: THE PATH TO RELIABLE COST-EFFECTIVE DECARBONIZED ENERGY SERVICE

Abstract: This paper provides a short summary of the chang- ing energy resource and energy demand characteristics in diverse social-ecological energy systems (SES). Examples are given of worldwide challenges created by the societal objectives to divert climate change, and to, at the same time provide reliable energy services at reasonable cost. Given unique temporal and spatial challenges of these systems, we suggest that one must from the beginning consider an SES as a social ecological technical system (SETS), and re-think producing, consuming and delivering en- ergy as a new complex operations and planning problem. If this is not done, it will become impossible to align often conflicting objectives. We describe how, starting from the first principles, one can utilise a unified modelling of general energy systems for implementing transparent data-enabled distributed protocols for interactive power balancing and delivery at the right rate. We document how having such data-enabled protocols would significantly increase the utilisation of the existing electric energy systems infrastructure, and provide signals for its enhancing at value. Potential benefits measured in terms of social welfare, service quality and cost are illustrated.

Index Terms: *rolling blackouts, social ecological energy systems (SES), social ecological technical systems (SETS), protocols for distributed autonomous electricity service, digitisation, Ex- tended AC Optimal Power Flow (XOPF), plug-and-play arhci- tectures, Dynamic Monitoring and Decision Systems (DyMonDS) framework, cyber-physical systems (CPS)*

---

[*] Marija Ilić, Massachusetts Institute of Technology, Cambridge, MA

I. INTRODUCTION

Currently we are witnessing worldwide difficult, often volatile, energy provision problems. During holidays US customers were asked to conserve power and reduce their heat; not long ago Texas consumers had no power during cold winter snap; Puerto Rico population repeatedly loses power during extreme weather conditions; many developing countries have been accustomed for a very long time to use electricity only when available, namely service being available only when generation is available. Europe has most recently been deprived of expensive energy services due to geopolitical conflicts, as have other war torn countries. There have also been service interruptions caused by physical and cyber attacks on infrastructure.

To make matters worse, these problems are becoming more frequent although only very few conventional energy resources are actually getting offline for retiring. They have so far fallen under the category of „very low probability high impact" events. The problem is likely to worsen as attempts are being made to meet zero carbon energy services as the generation mix becomes more intermittent and the conventional power plants no longer supply power.

A. The need for rethinking energy operations and planning paradigm

In parallel with these highly visible service problems, there have been ongoing R&D e fforts toward reverting cli- mate change by deploying many distributed energy resources (DERs), such as households with their own roof top solar photo-voltaic (PVs) and back-up generators; price-responsive demand consumption; even utilising very small storage appliances, such as HVACs, electric water heaters, electric vehicles (EVs), for regulating frequency and voltage caused by power imbalances around the scheduled generation for predictable system demand [1]. Probably the best known and the earliest was the homeostatic control vision by the late Fred Schweppe with his colleagues at MIT more than three decades ago [2]. Much R&D effort has gone since into conceptualising sensing and automated control of DERs, so that they self-adjust as per needed basis.

These concepts have been shown using simulations mainly, and by carrying out very few small scale pilot projects. Utilities operating distribution systems have not considered systematically new ways of integrating the effects of very large number of DERs when assessing options to serve their customers. Reasons for this are numerous, including: 1) wanting to carry out top-down service by pre-programming the equipment based on historical power usages; 2) thinking of these effects as having insignificant effects on electricity service; and, 3) not seeing the need to fix something that is not broken. Unfortunately, the current challenges with energy services clearly indicate that something is broken, and that there exists an obvious need to rely on all possible resources as system conditions vary. Notably, some utilities are working with their customers on installing higher efficiency electic loads, such as heat pumps; these are most frequently not programmed to respond to system conditions and/or price of electricity [3]. This means that they are not equipped with automation for adjusting when most needed. Electric distribution grids, in particular, can and should consider deployment of data- enabled normally-open switches (NoS) and/or normally-closed switches (NcS) which are likely to become instrumental in re-routing power within the distribution grid to accommodate power delivery from other resources when local resources fail to do so due to intermittent power provision or due to equipment failures. Research has shown that it is possible to assess the impact of certain number of such switches on the improvements in electricity service, notably during low prob- ability high impact events [4], [5]. Aggregation of many small geographically dispersed DERs is often not implementable because distribution grid protection is still programmed mainly under the assumption that power flows uni-directionally from a substation to the end users connected to the local feeders.

On the bulk power systems (BPS) side, there has been on- going research toward enhancing just-in-time)JIT), just-in- place (JIP) data-enabled decision-making computer applications to assist system operators to make the most out of what is available [9], [10]. Instead of utilising generation for the worst-case single, or double outage (($N-1$) or ($N-2$) reliability standards [6]) and requiring much reserve in case these occur, methods were proposed for doing optimisation to compute quickly the key constraints to feasible power delivery during these contingencies and actions to overcome by most effective adjustment of the remaining controllable equipment ratter than creating „proxy“ limits to physical limits of hardware, like transmission line flows [11], [12]. This can replace the need for conservative local reserve allocation. Instead, during extreme events reliable service can be provided at a regional level, rather than state by state. BPS operators and planners rarely account for effects of DERs at the point of connection (PoC) between them and distribution grids. Unfortunately, the same way as with distribution systems, implementing innovative solutions, in particular these low- hanging fruit decision-making software and statistical learning about the system demand and conditions, has been rather slow, almost non-existent. The (Independent)System Operators ((I)SOs) have continued to use DC power flow, and, in the electricity markets DC Optimal Power Flow (DC OPF), while fully aware of the fact that most binding constraints to delivering power over far electrical distances have been voltage/reactive power problems. The decisions on by how overcome voltage-related delivery problems between different supply-demand parts of the system are left to the (I)SOs; as such they cannot be reproduced, and have led to must run generation units, and out-of-market dispatch [8].

II. THE DANGER OF STATUS QUO AND POSSIBLE WAYS FORWARD

Utilities are still required to serve as the providers of the last resort. At the same time, they will have to, more often than in the past, deal with major weather-related service disruptions, because it is becoming harder and harder to accurately predict demand and plan for extreme events. Also, with the electrification, peak demand will increase, and probability of disruptions will increase significantly. This situation clearly points into the basic need to utilise all available resources as much as possible. In simple terms, it is insufficient to consider BPS level large-scale conventional generation as the only resources responsible for enabling reliable service. Given maturity of sensing and automation, utilities will do much better by transforming themselves into cyber-physical systems (CPS) in which data-enabled on-line decision-making is key to flexible utilisation, all else being equal. Reliable service and using clean resources do not have to be conflicting objectives. There exists a break-even point at which the cost of pollution balances with the ability to avoid service interruption. There exists also a way to assess different technologies, hardware and software, for their ability to enhance benefits in operations versus incremental cost of enhancing the infrastructure [13]. There exist even performance-based regulatory pricing, such as peak load pricing which establish value from these enhancements [14].

The time has come to think of electric energy service rather than kW hour as a volumetric quantity. Because of intermittency, and because of requiring both distribution systems and BPS to deliver power flow patterns for which they were not originally designed, the time has come to have operations and planning for best electricity service. Instead of building for assumed demand, it becomes essential to have interactive information exchange between grid users and the grid operators. This must be done at the level of granularity sufficient to extract the most out of what is available.

A. Today's approach to operations and planning for reliable and resilient electricity services

The bulk power systems (BPS) have different planning and operating practices than the distribution systems, as summarised next.

1) Basic functions performed by the control centres in BPS: Today BPS have established computer applications in their control centres for meeting the NERC/FERC reliability criteria [6]. To briefly review, and set the basis for understanding the evolution and new opportunities offered by the increasing penetration of DERs at the distribution system levels, we take a step back and recall that in today's industry electricity service is provided by performing five (5) functions. These are: 1) scheduling controllable conventional generation to supply predictable system demand; 2) supplying a bit more generation to compensate for Joule losses in the delivery grid;

3) scheduling so that the power delivery is feasible, namely that there is no grid congestion, namely the power delivery is within the allowable thermal line flow limits and equipment voltage constraints; 4) having sufficient regulation reserve to compensate hard-to-predict system demand deviations from predicted demand patterns; and, 5) having sufficient reserve to not interrupt customers at least for 30 minutes following any single, or double, BPS outage. The control centres of a BPS have computer applications for assisting system operators with performing these functions [15].

2) Basic practice in operating distribution systems: Notably, it has been shown that there is very little assurance that small distribution grid users will have the reliability standards required by their states, such as SAIDI and SAIFI, met based on the BPS control [16]. Despite this recognition, distribution systems are mainly based on pre-programming controllable equipment for seasonal demand, and under the assumption that the only power comes from the substations connected to the BPS and that these point of contact (PoC) are effectively ideal source which provide perfect AC frequency and voltage while sending power to the distirbution systems. Minor service interruptions in localised part of the grid are created mainly by trees touching equipment during bad weather. Utility, sooner or later, learns about the service interruption and sends engineers to repair the failed equipment. As a rule, there are no alternate paths from PoC to small end users, and when a substation itself gets disconnected, all customers lose power, the case of recent North Carolina service interruptions [17]. Substations are becoming favourite places for both physical and cyber attacks, and, they mainly lead to major service interruptions. The BPS cannot prevent this problem from happening since there is simply no viable alternate path. NoS and NcS are instrumental to supporting power delivery from other neighbouring substations [4], [5].

III. DIFFERENT WAYS OF ENABLING DECARBONIZATION

To move forward, it is necessary to establish systematic guidelines for integrating new technologies, in particular clean DERs within the legacy electric energy systems. These are being added to both the BPS and into lower-voltage level grids, such as distribution systems and even by building local microgrids. Since many of these new resources are often third-party-owned, grid planners and system operators need to establish transparent, technically- and economically- justifiable protocols for their integration. As described earlier in this paper, today's interconnection standards are system- specific and generally do not provide quantifiable ways of determining ranges of energy, power, reactive power and their rates of change so that feasible and robust electricity service is ensured. A particular challenge concerns very high-impact low-probability events, which are becoming more frequent as a result of extreme weather and hard-to-predict cyber- and physical-infrastructure attacks [18] One can not neglect possibility of wide-spread life threatening events which can be created by targeted cyber attacks and even electromagnetic pulse storms, documented through state exploration programs. While the industry is currently not charged with preparing for higher than (N – 2) events, it is important to be prepared for providing at least critical service during such extreme events. More generally, as system conditions vary, it is necessary to support gradual

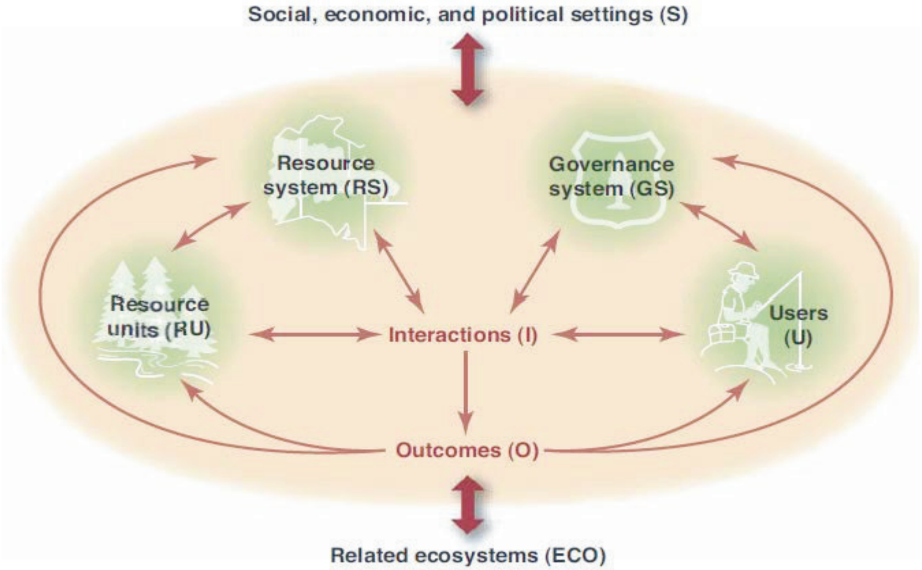

Fig. 1. Basic social-ecological system core variables and their interactions [19]

degradation of service rather than have wide- spread loss of service. Later in this paper we describe how this might become possible with the approach proposed here. Although one of the main ideas in this paper is to describe how distributed automation and digitisation can play a major role in making the most out of any given social ecological energy system, for this to be done in an effective way it is necessary to pose this objective in the broader context as with any other technologies.

IV. SOCIAL ECOLOGICAL ENERGY SYSTEMS (SES)

We start by posing the problem of enabling reliable and cost-effective electricity service as the problem of making energy systems sustainable in the same sense as any other SES. This is done by viewing these systems as complex systems comprising many diverse ecological groups of resources (RS); and socially-diverse groups of users (U), all governed by a particular governance system (GS). This view is much the same way as Elinor Ostrom used to introduce her general framework for assessing sustainability of an SES Figure 1 [19]. The RS, U, and governance system (GS) form core variables of an SES, and their attributes which determine sustainability represent second-level core variables. Notably, there exist key second-level variables contributing the most to the overall sustainability of an SES, Table 1 in [19].

In this section we introduce a generalized architecture of the evolving energy systems which, instead of RS, U and GS comprise physically interconnected subgroups of resources and users by means of man-made infrastructures, with their own sub-objectives and data-enabled decision-making and information exchange with other subsystems. We then describe how to use the general notion of second-order core variables introduced for any SES, and give examples of such variables for assessing performance of any given social-ecological- technical system (SETS). We then discuss potential role of governance system in SETS for enabling good performance, we give examples of three qualitatively different architectures and the interaction variables within these SETS.

A. Fundamental complexity of an end-to-end electric power interconnection SETS architecture

The electric power-, gas- and other energy carrier grids are man-made physical- and cyber-network infrastructures enabling the interactions between RS and U in a general electric energy system sketched in Figure 2 [9].

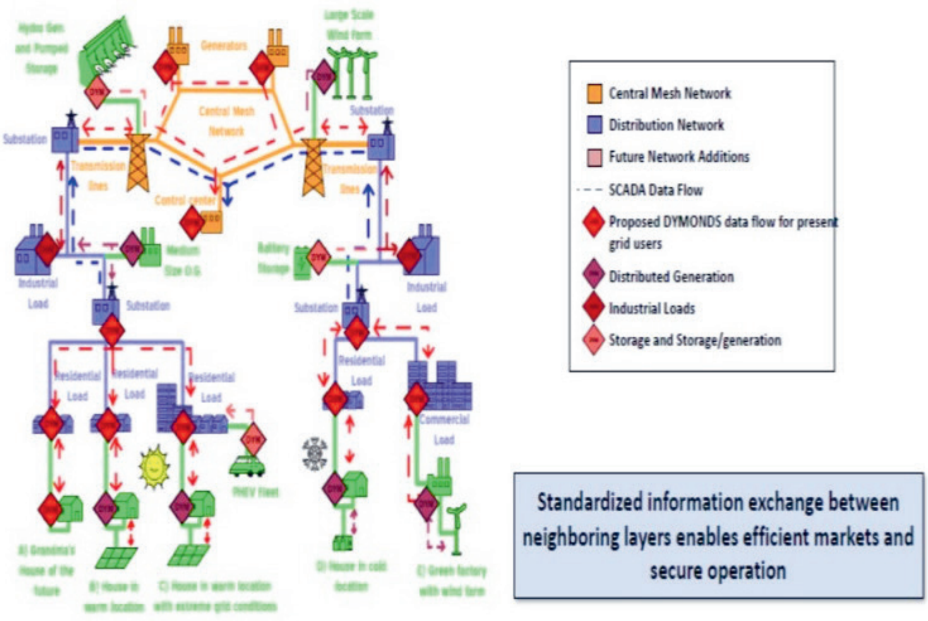

Fig. 2. Fundamental complexity of an end-to-end physical-/cyber electric energy system [9]

The man-made power grid makes the representation of an SETS more complex than the representation of an SES shown in Figure 1. Shown is the physical infrastructure which is generally a physical interconnection of the central extra-high-voltage (EHV) mesh network (orange solid lines), via step-down transformers to high voltage (HV) sub-transmission and medium voltage (MV) distribution radial grids (purple solid lines) and further down to low voltage (LV) distribution grids and microgrids [9]. Dotted red and blue lines represent the SCADA data flow, in today's bulk power systems and the missing in lower voltage networks, respectively. The red „dymonds“ represent cyber (data sensing, processing in support of decision-making and control) embedded within the core variables. Today most of the BPS core variables (RS and U) have somewhat standardized cyber, including the Energy Management System (EMS) collecting SCADA data, using different computer applications (such as economic dispatch, power flow analysis, and alike) and sending commands for generation scheduling. Finally, it can be seen from Figure 2 that there are many new DERs with their own cyber, mainly embedded closer to the small end users. The spatial

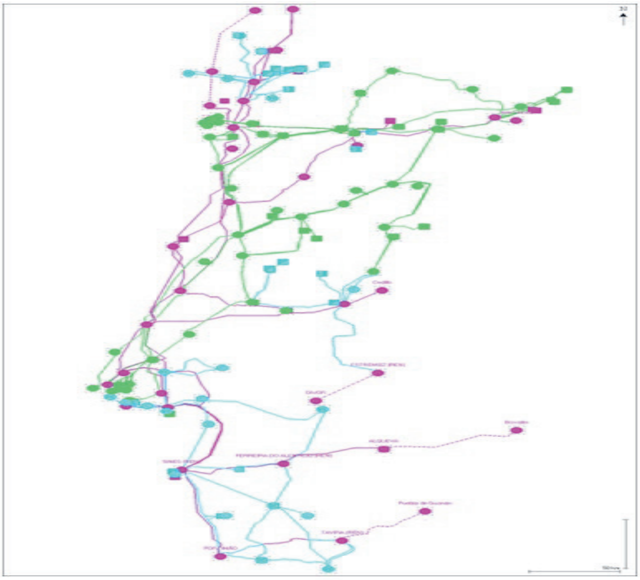

Fig. 3. Real-world distribution feeder in Portugal [9]

complexity of an SETS is two-fold: Horizontally, there are several interconnected BAs, as shown in Figures 3 and 5, each of which with the basic hierarchical structure shown in Figure 2. Vertically, in each BA there are many

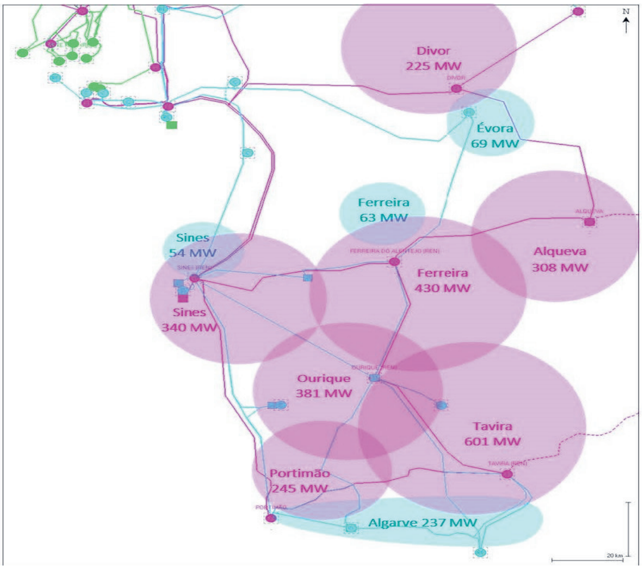

Fig. 4. Candidate solar-based iBAs seeking interconnection with the main BPS in Portugal

Fig. 5. The US BPS interconnection comprising several large BAs [6]

candidate iBAs. Shown in Figure 4 are candidate solar iBAs seeking connection to the main grid. In today's industry this very complex end-to-end SETS comprises large subsystems known as the Balancing Authorities (BAs) shown in Figure 5 for the US interconnected system. Integration of third-party sub-systems shown in Figure 4 leads to embedded nested architecture of smaller intelligent Balancing Authorities (iBAs) within the existing BAs. Shown in Figures 6 and 7 are a general nested architecture of the evolving SETS and a small example of transforming RS, U interconnected by electric power grid into interconnected iBAs, respectively [20], [21].

B. *Key role of aggregating „flat“ SES to multi-layered inter- acting composition of iBAs*

The hierarchical complexity in today's industry in systems comprising horizontally-composed BAs and vertically- organized transmission- and distribution-systems within BAs, has been managed by spatially and temporally decom- posing these entities and managing each level hierarchically under major assumptions, such as weak spatial coupling between horizontally-organized BAs, and temporally- decomposed vertically-organized entities. They cyber designed has greatly simplified under these assumptions [22].

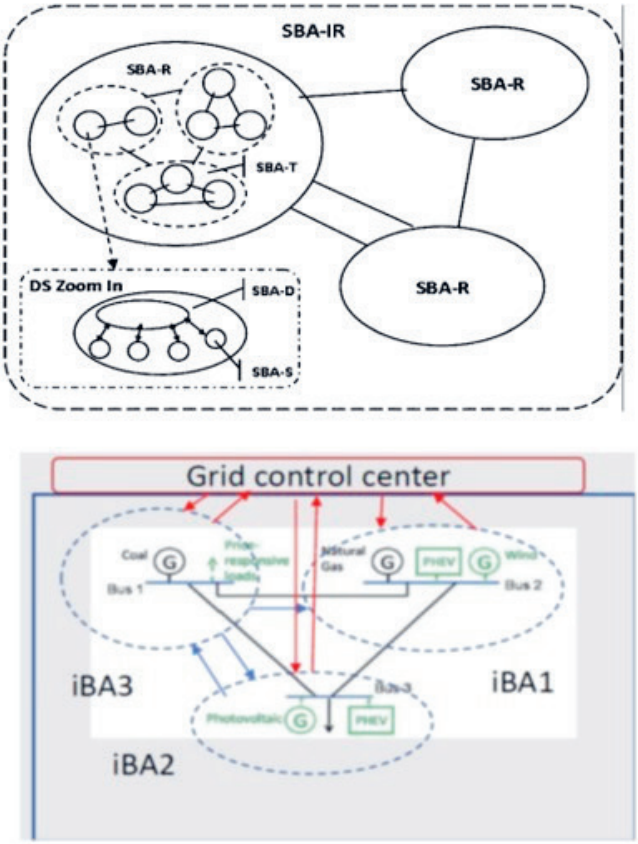

Fig. 6. Nested end-to-end architecture comprising lower levels iBAs and higher level larger BAs [9]

As the industry is evolving into a composition of interacting iBA s, it is no longer possible to ensure validity of these hierarchical arrangements. Instead, hierarchies are becoming nested, Figure 6 and are interacting more dynamically. Shown in Figure 7 is a sketch of a small BPS SETS comprising conventional RS and U (drawn in black). Embedded into this BPS are DERs of diverse types (green lines), including price responsive demand. it is then shown how this „flat“ SETS with clearly defined RS and U, evolves into a nested system with aggregated iBAs.

In summary, wes tress that one of the most important second-level core variables are clearly identified boundaries of the groups of components with common performance objectives. This is teh main reason for having introduced a notion of technology-agnostic iBAs, and then defining their interaction variables with the rest of iBAs within an SES. Unique to the energy systems is that their alignments must be temporal, spatial and functional, otherwise the system may not be feasible and/or it may be overly sensitive, non- robust to even small deviations from assumed conditions and specifications.

Once this is understood, it becomes possible to assess different hardware and software technologies which can help the given SES become more sustainable. This then becomes the problem of designing an SETS for sustainability. This high-level conceptualisation helps tremendously in assessing potential of different technologies for making the most out of what is ecologically available and socially acceptable to the governance and the users.

V. UNIFIED APPROACH TO MODELLING THE INTERACTION DYNAMICS WITHIN AN ENERGY SETS

So far we have conceptualized an architecture of any SETS as a generalization of an SES into a multi-layered system comprising interconnected iBAs. In order to capture their unique temporal and spatial characterisation we next view them as complex end-to-end interactive multi-layered dynamical systems comprising diverse subsystems, named, iBAs. These iBAs, much the same way as the core variables in any SES, are characterized by their second-level core variables. We observe that the second-level core variables most desired to support sustainable SETS are the ones which align the technical, economic and environmental sub-objectives of iBAs with those of the other iBAs. Notably, selecting man- made technologies to support sustainable interactions requires modelling of the interactions of iBAs with other iBAs. To assess how well the interactions are aligned, we utilize a unified notion of interaction variables for any given iBA in terms of physically interpret-able energy dynamics. These are based on the first principles and are technology and system- agnostic and can support performance at value, discussed next.

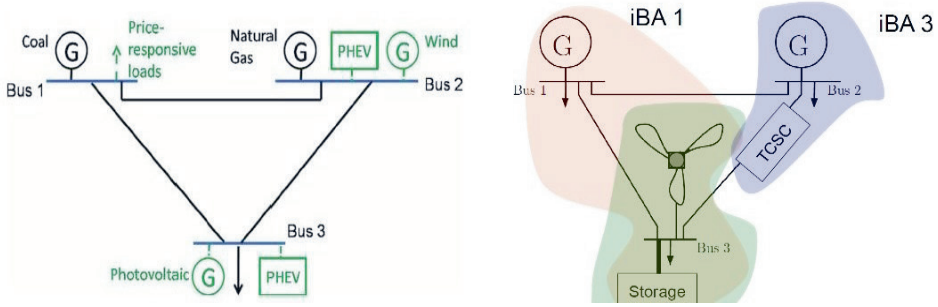

Fig. 7. The evoluting from „flat“ SES into a composition of interacting iBAs [21]

A. Technology- and system-agnostic interaction variable representing iBAs

The aggregate variables characterizing any iBA are stored energy and rate of change of stored energy. The dynamics of these aggregate variables have been shown to satisfy the following model

$$\frac{dE(t)}{dt} = -\frac{E}{\tau} + p(t) \quad (1)$$

$$\frac{dp(t)}{dt} = 4E_t(t) - \dot{q}(t) \quad (2)$$

where $E(t)$, and $p(t)$ are aggregate state variables, stored energy and rate of power coming into the iBA, respectively. The term $-\frac{E}{\tau}$ represents τ Joule losses of the iBA, the term $E_t(t)$ represents energy in tangent space, and it has an intuitive interpretation related to exergy, namely to the potential to do work [24]; the term $\dot{q}(t)$ represents rate of change of power which does not perform real work, namely it reflects the impossibility to do work without increasing entropy, known as anergy [24]. Power $p(t)$ can be sent from the neighbouring iBAs $P(t)$, or it can be injected internally by some local controller $P_u(t)$, namely

$$p(t) = P(t) + P_u(t) \qquad (3)$$

Similarly, rate of change of generalised reactive power [23] can be decomposed into the component stemming from the neighbouring iBAs $\dot{Q}$ (t) and/or from the internal controller $\dot{Q}$ $u(t)$, namely

$$\dot{q}(t) = \dot{Q}(t) + \dot{Q}_u(t) \qquad (4)$$

Our earlier work concerning interaction variables was recently summarized in detail [25]. It is described in this article how, looking in a hindsight, one can start from the first principles and define interaction variable as an aggregate variable whose properties are a direct expression of conservation of energy dynamics. In short, when disconnected from the rest of the system, an iBA conserves its own energy. When connected to the other iBAs, it must satisfy instantaneous power balancing and the rate of change of generalised reactive power It can be seen from the dynamics of aggregate variables $E(t)$ and $p(t)$ that they are function of themselves and the rate of change of iBAs interaction variable $\dot{z}(t)$ where

$$\dot{z}(t) = \left[P(t)\ \dot{Q}(t)\right] \quad (5)$$

While iBAs can be quite complex themselves, their interaction with the rest of the system can be captured by writing the dynamics of the aggregate variables in a modular way for each iBA, and then stating that in order for the interconnected system to be feasible and stable the rate of change of their interaction variables must balance. For the simplest case of one resource (RS), interconnected via transmission line (iBA 1) to one user (U) (iBA 2) the interconnected system model takes on the form

$$\frac{dE_1(t)}{dt} = -\frac{E_1}{\tau_1} + p_1(t) \quad (6)$$

$$\frac{dp_1(t)}{dt} = 4E_{t,1}(t) - \dot{q}_1(t) \quad (7)$$

$$\frac{dE_2(t)}{dt} = -\frac{E_2}{\tau_2} + p_2(t) \quad (8)$$

$$\frac{dp_2(t)}{dt} = 4E_{t,2}(t) - \dot{q}_2(t) \quad (9)$$

When there are no internal controls inside iBAs, $p_1(t) = P_1(t)$, $p_2(t) = P_2(t)$, $\dot{q}_1(t) = \dot{Q}_1(t)$ and $\dot{q}_2(t) = \dot{Q}_2(t)$. For the interconnected system to be feasible rate of change of interaction variables must be equal, namely

$$P_1(t) + P_2(t) = 0 \quad (10)$$

and

$$\dot{Q}_1(t) + \dot{Q}_2(t) = 0 \quad (11)$$

In our work up to date we have shown that it is sufficient to characterise outputs of any component comprising the system. Coupled model given in Equations (6)–(11) is the new unified energy dynamics model.

VI. PRINCIPLES OF DATA-ENABLED SENSING AND CONTROL FOR SETS

The piecemeal process of decarbonization is already under way, without having a holistic understanding of its objectives and feasibility of achieving it. The debates have become highly ideological and biased, ranging from extreme proposals that there will be one solution solving it all; for example, proponents of demand side efficiency and response are exchanging endless emails focusing on this particular aspect of solution [26]; there are also many expressing concerns that the climate change objectives are simply not achievable [27].

To overcome this endless non-constructive debate, in this paper we propose that it is possible to utilize the unified modelling of the evolving electric energy systems to assess their sustainability. Of particular interest is to understand potential of innovation, both hardware and software, in enhancing their performance. While the qualitative characterization of performance is very similar to the one put forward by Elinor Ostrom, the unique challenges in these systems come from the need for quantifying the desired second-level core variables, key to good performance of any SES. This can be done by assessing spatial, temporal and functional alignments of the interactions between R, U and GS, shown in Figures 1 and 2 represented as interactive mathematical models of type given in Eqns. (6)– (11). These models can be used to interactively in feed-forward manner check the power flow feasibility when iBAs are interconnected [28]. This recognition becomes the key to embedding most effective man-made technologies and transform any given SES into as sustainable as possible SETS. Enabling an SES with many man-made infrastructures and their data-faciliated functionalities, sketched in Figure 2 [9]. On the contrary, if these interactions are not aligned, much will be wasted. The main objective of distributed automation embedded within the R, U, GS is to enable implementation of these alignments to as large extent as possible.

The process of assessing potential of technological innovations in electric energy systems can be supported by proposing the following three basic principles [29].

— Characterize all (group of) component(s) (subsystem) in terms of transparent, unified outputs for their technical, economic, and environmental potential performance when connecting to the system.

— Generalize today's Supervisory Control and Data Acquisition (SCADA) of today's BPS to support protocols (interactive multi-layered information exchange) over multiple time horizons, in a feed-forward and feedback manner, over a stratum of time horizons for which performance of the system is assessed.

— Establish data-enabled assessment tools based on conditions which are sufficient to ensure feasible and robust preference of the interconnected systems. Shown in Figure 2 for any time interval T in terms of a triplet interaction outputs energy ET, power PT, and rate of change of reactive power $\dot{Q}_T$ [28].

VII. GENERAL DYNAMIC MONITORING AND DECISION SYSTEMS (DYMONDS) FRAMEWORK FOR ASSESSING PERFORMANCE OF ANY SETS

As described above, any given electric energy system can be thought of as a data-enabled complex interactive dynamical system comprising many iBAs. Conceptualizing the architecture this way is extremely helpful because it becomes possible to understand performance sub-objectives of different iBAs, and model their interactions. It becomes possible to think of the problem of feasible and sustainable SETS as the problem of technological enhancements most effective in aligning interacting resources, groups of resources, groups of users, within a given governance system. Governance rules, rights and regulations (3Rs) themselves can be assessed and further evolved to give incentives for supporting the second- order variables most important for sustainability.

A. Assessing different architectures for their support of decarbonization

Having taken this view it becomes quite straightforward to assess next the same SES for its performance depending on the technological solutions. Just to illustrate, we consider next

1) an SES without any technological solutions utilized; 2) SES with today's centralised operations and planning; 3) entirely decentralised; and 4) enabled by an interactive DyMonDS which we have conceived some time ago [9], [30]. It is quite important to recognize that there is no universal technology which makes any SES system most sustainable. This, in turn, implies that different man-made power grids for enabling physical interactions between R and S within a given GS lead to different performance.

— **Social ecological energy system** without any man-made infrastructures is clearly not feasible nor robust with respect to even small disturbances. Only energy from local resources to the users can be provided.

— **SES with today's centralised operations and planning** Shown in Figure 2 is a typical modern-day electric energy system with large conventional resources, interconnected by the EHV/HV electric power grid and connected further through substations to the large number of users in local distribution systems. In the past users have consumed energy without receiving much feedback from the utilities concerning the need to adjust their consumption. These systems have provided electricity service by unidirectional sending power from resources to the users. A quick look at their second-order variables reveals that there has not been significant temporal nor spatial alignment between the resources and users. The alignment has been achieved mainly by building a physically- strong electric power grid and not relying on just-in-time (JIT), just in place (JIP) just-in context (JIC) dynamic alignments of resources and users. Many other second- level variables key to making the SETS sustainable are generally not a part of planning and operating practices in today's industry. The operating and planning standards are fundamentally based on the worst-case deterministic approach which requires setting aside large reserves [6]. The reserves are typically not used in real-time except when certain worst case event, such as large resource or transmission line contingency, takes place. Much has been written by this author to document missed opportunities from not relying on more dynamic allocation of such reserve as the operating conditions change [20], [33]–[35].

As the conventional power plants are being retired, the more environmentally-friendly intermittent resources, such as large utility-scale wind- and solar-power plants are being deployed, the need for more flexible utilization of what is available by means of data-enabled software for aligning interaction variables within the changing SETS becomes self-evident [7], [32]. Notably, even the next wave of smaller-scale nuclear reactors and other promising nuclear technologies will require more flexible system integration to avoid tripping these units through unaligned interactions with the rest of the system. The problem of data-enabled integration of growing scale of safe and reliable nuclear power deployment in support of decarbonization is an important R& D question which must be given major attention.

This paper is written in part by wanting to point out this low-hanging opportunities which can be made a reality in relatively short term manner. Pursuing top-down highly centralised deterministic approach will make it hard to implement gradual degradation of service during extreme rare-events such as hurricanes [32]. Planning will require much large-scale storage to manage temporal uncertain- ties and huge investments in power grid infrastructure to deliver power from often distant intermittent resources, including EHV DC backbone grid estimated to cost more than $200 billion dollars in the US and similarly in Western Europe.

— **Competitive decentralised operations and planning** is considered as an alternative architecture in which many distributed, often small-scale energy resources (DERs), including demand response [26], are placed locally close to the users and are intended to serve them by forming local microgrids. This approach of defecting the utility grid and each household, or neighbourhood, becoming an iBA and serving itself using solar PVs, back-up generation and storage (thermal, EVs), is appealing to many. However, this architecture may end up experiencing significantto periodically post the so-called hosting capacity for such resources [36].

NERC BA standards for AGC in place today are currently being extended to non-utility-owned iBAs. Such stan- dards effectively require each iBAs to cancel the changes seen through the interactions with the neighbouring iBAs. This architecture would become the one of many decoupled iBAs, a highly inefficient and unsustainable solution [31]. This architecture itself goes against the very funda- mentals of supporting cooperative alignment of second- order variables needed for efficient decarbonization. Becasue of this, the emerging decentralzied architectures require much rethinking about governance and design of 3Rs in which all iBAs have clearly defined boundaries and are incentivized to go beyond strictly competitive integration. A drastic example is the problem of expecting today's utilities to still remain providers of the last resort, when local resources fail to provide expected service. Utilities can simply not do this and stay financially feasible as the scale of DER deployments increases to meet the environmental objectives, another major R&D question which must be studied.

— **DyMonDS-based architectures** are a natural extension of today's utility systems needed to plan and operate in a sustainable manner large amounts of clean DERs within low voltage distribution grids and re configurable microgrids. This must be done without endangering the backbone bulk power system production, consumption and delivery of power from large utility-scale, often electrically far from the substation level points of con- tact (PoC) with lower voltage level substations. As the utility BPS level power flow patterns change due to changing generation and demand mix, there are already major concerns that the reserves required in the past are significantly reduced. An obvious short-term solution to this problem is to begin to enable lower-level DERs and users, and the grid itself with the distributed interactive data-enabled minimally coordinated autonomy [29]. Instead of setting rigid interconnection standard constraints on hosting capacity, it is important to have a DyMonDS-based system in place in which self- adaptation and protocols using minimal information ex- change in terms of interaction variables support their cooperative alignments. Due to space limitations we do not discuss how such protocols led themselves to highly distributed autonomous multi-layered control. The higher layers utilize unified energy dynamics for deriving control logic needed to align the rate of change of interaction variables $\dot{z}(t)$ defined in Eqn. (5). The energy dynamics of the interconnected systems shown in Equations(6)–(11) lends itself to defining the control problem operating problems in real time without embedded data-of aligning interaction variables $\dot{z}(t)$ among iBAs as enabled support to self-adjust and align local resources and users. At present, there are interconnection standards which limit the presence of such local DERs in the distribution systems. Utilities, on the other hand, are required a provable linear control problem, it becomes possible to have provable performance in an otherwise highly complex multi-layered system, and build confidence in the performance of novel re configurable microgrids, for example [37]–[39]. The higher layer control design of aligning energy dynamics is technology agnostic. The Implementation of the actual internal control of $P_u(t)$ and $\dot{Q}\ u(t)$ (recall Equations (3) and (4)) is technology-specific, and can be kept proprietary to the manufacturers as long as they can specify the ranges of rate of change of their interaction variables prior to interconnecting and, moreover, participate in self-adjusting to the rest of the system.

VIII. A PATH FORWARD TO SUSTAINABLE DECARBONIZATION: DISTRIBUTED AUTONOMY WITHIN THE DYMONDS FRAMEWORK

DyMoNDS architecture helps make the case for embed- ding systematically data-enabled management of the changing electric energy systems. Having a flexible JIT, JIP, JIC service is paramount to having desired second-order variables in an SETS. Characterising the iBAs, as these evolve and become nested within the existing utilities, requires major data-enabled internalization by diverse iBAs themselves and minimal infor- mation exchange in terms of their interaction variables. This begins to form the kernel of distributed interactive autonomy, in which having key information contributes in significant ways to decarbonization. There is a rapidly growing awareness of the need for end-to-end information exchange. Without systematic foundations for protocols this quickly leads to an open ended complexity in which information is not utilized for the right functionalities required to have a sustainable SETS. In DyMoNDS-based cyber-physical ecosystem data begins to be utilized systematically, to list just a few examples:

— Use of weather information for predicting clean power generation; equipment status; system demand

— Adaptive load management for dynamic balance of sup- ply and demand with least expensive and cleanest re- sources

— Minimizing the need for stand-by reserves while still ensuring reliable high QoS electricity service (implementable preventive and corrective reserves)

— Minimizing the need for long-term capacity

— Enabling many DERs to participate in grid congestion management

— Data-enabled management of controllable T&D equipment to support most sustainable social ecological energy systems

— Resilient service during extreme events

The vision put forward in this paper represents qualitatively different ways of data-enabled electric energy services. To manage more complex design and operations objectives, one must understand the trade-off between communication/control complexity; market, technical outcomes; and

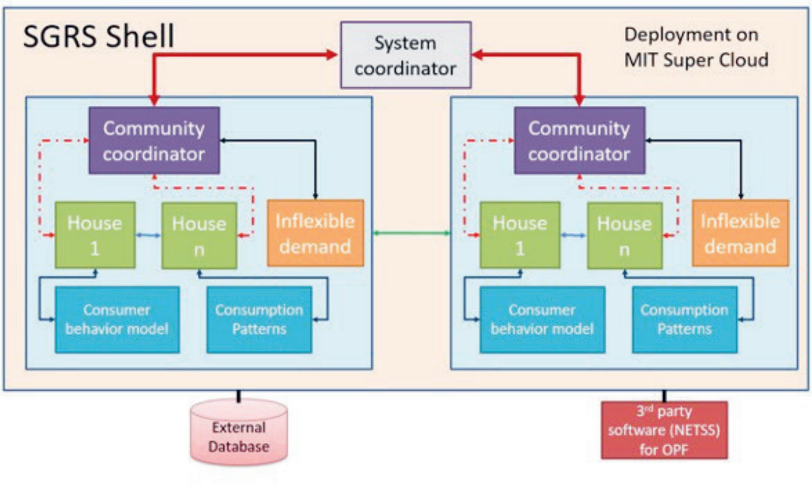

Fig. 8. Embedded IoT/ML/AI DyMonDS-based computer platform [42]

environmental effects. These are truly exciting complex systems problems whose solutions offer hidden value of high tech without having to be a domain expert in specific generation, distribution, consumption technology. Instead there is much need and opportunity to use knowledge from dynamical systems, control, numerical methods, analytics, machine learning and, ultimately, AI to enable feasible, efficient and clean services to the extent possible.

Shown in Figure 8. is a sketch of our Smart Grid in a Room Simulator (SGRS) which we have worked on developing throughout the years of building our knowledge in support of DyMonDS framework. [40]. It has become clear over the years of this research that the grid analytics becomes crucial for effective use of digitalization. Pursuing a systematic path from gathering data to IT-enabled protocols in support of targeted system performance can have a potentially large impact on decarbonization process. Shorter term it can significantly help with resilient/robust electricity service at the affordable price. Notably, DyMonDS framework lends it self quite naturally to cyber secure implementation of data-enabled re-integration of DERs into legacy electric energy systems [41]. There are some examples of pilot proof-of-concept use of digitalization. How- ever, scaling up in transparent ways requires sound principles for setting minimally required information exchange proposed in this paper. DyMonDS framework supports solving a long- standing practical problem of growing households in a plug- and-play manner [43] without causing reliability problems, and doing this in a cooperative efficient manner. This knowledge offers a major opportunity which may not be ever materialized unless a focused effort to setting up protocols based on the three simple principles put forward in this paper is pursued. Perhaps the most urgent is to focused efforts on transforming a SGRS into a digital twin which might work [42]. Having such facility will make many perhaps difficult-to-absorb concepts put forward in this paper tangible illustrations using a carefully designed digital twin.

REFERENCES

[1] Rohlfing, Eric. „The ARPA-E Mission.“ In 2015 ERC. 2015.

[2] Schweppe, F. C., Tabors, R. D., Kirtley, J. L., Outhred, H. R., Pickel, F. H., & Cox, A. J. (1980). Homeostatic utility control. IEEE Transactions on Power Apparatus and Systems, (3), 1151–1163.

[3] Love, Jenny, Andrew ZP Smith, Stephen Watson, Eleni Oikonomou, Alex Summerfield, Colin Gleeson, Phillip Biddulph et al. „The addition of heat pump

electricity load profiles to GB electricity demand: Evidence from a heat pump field trial." Applied Energy 204 (2017): 332–342.

[4] Junlakarn, Siripha, and Marija Ilic. „Toward implementation of the reconfiguration for providing differentiated reliability options in distri- bution systems." In 2014 IEEE PES General Meeting— Conference & Exposition. IEEE, 2014.

[5] Junlakarn, Siripha, and Marija Ilic. „Provision of differentiated reliabil- ity services under a market-based investment decision making." IEEE Transactions on Smart Grid 11, no. 5 (2020): 3970–3981.

[6] Watson, W. F. (2017). NERC mandatory reliability standards: A 10- year assessment. The Electricity Journal, 30(2), 9–14.

[7] Cvijic, S., Ilic, M., Allen, E., & Lang, J. (2018, October). Using extended ac optimal power flow for effective decision making. In 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe).

[8] Mukerji, R., Merrill, H. M., Erickson, B. W., Parker, J. H., & Fried- man, R. E. (1991). Power plant maintenance scheduling: optimizing economics and reliability. IEEE Transactions on Power Systems, 6(2), 476–483.

[9] Ilic, M. D. (2010). Dynamic monitoring and decision systems for enabling sustainable energy services. Proceedings of the IEEE, 99(1), 58–79.

[10] Ilic, Marija. „3Rs for Power and Demand." Public Utilities Fortnightly Magazine 61 (2009).

[11] Ilic, M., & Jaddivada, R. (2022). Modeling and Control of Multi- Energy Dynamical Systems: Hidden Paths to Decarbonization. arXiv preprint arXiv: 2207.08370.

[12] Ilic, Marija D., and Pedro MS Carvalho. „From hierarchical control to flexible interactive electricity services: A path to decarbonisation." Electric Power Systems Research 212 (2022): 108554.

[13] Ilic, M., & Gough, M. (2022). Interactive Planning and Operations using Peak Load Pricing in Distribution Systems. arXiv preprint arXiv: 2212.02145.

[14] Crew, M. A., Fernando, C. S., & Kleindorfer, P. R. (1995). The theory of peak-load pricing: A survey. Journal of regulatory economics, 8(3), 215–248.

[15] Ilic, M., Galiana, F., and Fink, L. (Eds.). (2013). Power systems restructuring: engineering and economics. Springer Science & Business Media.

[16] Arce, J. R., Ilic, M. D., & Garce ́s, F. F. (2001, July). Managing short-term reliability related risks. In 2001 Power Engineering Society Summer Meeting. Conference Proceedings (Cat. No. 01CH37262) (Vol. 1, pp. 516–522). IEEE.

[17] https://nsjonline.com/article/2023/01/n-c-utilities-commission-hears-from-duke-energy-on-christmas-blackouts/

[18] Weiss, Joseph. Protecting industrial control systems from electronic threats. Momentum Press, 2010.

[19] Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. Science, 325(5939), 419–422.

[20] Ilic, M., and Liu, S. (2012). Hierarchical power systems control: its value in a changing industry. Springer Science & Business Media.

[21] Baros, S., and Ilic, M. (2014, July). intelligent Balancing Authorities (iBAs) for transient stabilization of large power systems. In 2014 IEEE PES General Meeting— Conference & Exposition (pp. 1–5). IEEE.

[22] Ilic, M. D., & Zaborszky, J. (2000). Dynamics and control of large electric power systems (p. xviii). New York: Wiley.

[23] Wyatt, J. L., and M. Ilic. „Time-domain reactive power concepts for nonlinear, nonsinusoidal or nonperiodic networks.“ In IEEE interna- tional symposium on circuits and systems, pp. 387–390. IEEE, 1990.

[24] Ilic, Marija D., and Rupamathi Jaddivada. „Multi-layered interactive energy space modeling for near-optimal electrification of terrestrial, shipboard and aircraft systems.“ Annual Reviews in Control 45 (2018): 52–75.

[25] Marija Ili/'c, Interaction variables-based Modelling and Control of Energy Dynamics, in Women in Power, Springer Nature Switzerland AG, 2023 (to appear)

[26] electricity-brain-trust@googlegroups. com

[27] https: //www. wsj.com/articles/the-christmas-electric-grid-emergency—11672091317

[28] Ilic, Marija D., and Rupamathi Jaddivada. „Fundamental modeling and conditions for realizable and efficient energy systems.“ In 2018 IEEE conference on decision and control (CDC), pp. 5694–5701. IEEE, 2018.

[29] Marija Ilic and Donald Lessard, A distributed coordinated architec- ture of electrical energy systems for sustainability, EESG@MITWP- dec302020.

[30] Ilic, Marija D. „Toward a unified modeling and control for sustainable and resilient electric energy systems.“ Foundations and Trends® in Electric Energy Systems 1.1–2 (2016): 1–141. Ilic, M. D., & Liu, Q. (2012). Toward sensing, communications and control architectures for frequency regulation in systems with highly variable resources. In Control and optimization methods for electric smart grids (pp. 3–33). Springer, New York, NY.

[31] M. Ilic, R. S. Ulerio, E. Corbett, E. Austin, M. Shatz, and E. Limpaecher, „A framework for evaluating electric power grid improve- ments in Puerto Rico,“ 2020.

[32] Ilic, M., Xie, L., & Liu, Q. (Eds.). (2013). Engineering IT-Enabled sustainable electricity services: The tale of two low-cost green Azores islands (Vol. 30). Springer Science & Business Media.

[33] Ilic, M., Cvijic, S., Lang, J. H., Tong, J., & Obadina, D. (2015, July). Operating beyond today's PV curves: Challenges and potential benefits. In 2015 IEEE Power & Energy Society General Meeting (pp. 1–5). IEEE.

[34] Ilic, Marija, Sanja Cvijic, Jeffrey H. Lang, and Jiangzhong Tong. „Op- timal voltage management for enhancing electricity market efficiency.“ In 2015 IEEE Power & Energy Society General Meeting, pp. 1–5. IEEE, 2015.

[35] Ilic, M. D., Jaddivada, R., & Korpas, M. (2020). Interactive protocols for distributed energy resource management systems (DERMS). IET Generation, Transmission & Distribution, 14(11), 2065–2081.

[36] Jaddivada, Rupamathi, and Marija D. Ilic. „A feasible and stable distributed interactive control design in energy state space.“ In 2021 60th IEEE Conference on Decision and Control (CDC), pp. 4950–4957. IEEE, 2021.

[37] Miao, Xia, and Marija D. Ilic. „High Quality of Service in Future Electrical Energy Systems: A New Time-Domain Approach.“IEEE Transactions on Sustainable Energy 12, no. 2 (2020): 1196–1205.

[38] Ilic, M. D., & Jaddivada, R. (2021). Making flying microgrids work in future aircrafts and aerospace vehicles. Annual Reviews in Control, 52, 428–445.

[39] Ilic, Marija, M. Wagner, F. Franchetti, K. Bachovchin, R. Jaddivada, S. Ray, Jonathan Donadee et al. „Smart grid in a room simulator-sgrs.“ National Institute of Standards and Technology, Tech. Rep (2016).

[40] Marija Ilic, Cyber secure Dynamic Monitoring and Decision Systems, MIT patent filing, 2022.

[41] Ilic, M., Jaddivada, R., & Gebremedhin, A. (2023). Unified modeling for emulating electric energy systems: Toward digital twin that might work. In Research Anthology on BIM and Digital Twins in Smart Cities (pp. 107–135). IGI Global.

[42] M. D. Ilic, Miao, X. and Jaddivada, R., „Plug-and-Play Reconfigurable Electric Power Microgrids,“ U. S. Patent 10,656,609, issued May 19, 2020.