A Decision-Making Framework and Simulator for Sustainable Electric Energy Systems

Marija D. Ilić, Fellow, IEEE, Jhi-Young Joo, Student Member, IEEE, Le Xie, Member, IEEE, Marija Prica, Student Member, IEEE, and Niklas Rotering, Student Member, IEEE

Abstract—In this paper, we propose a new framework for the organization of the electric power industry, based on extensive use of information technology (IT) and on interactive decision making, where consumers and distributed producers join the traditional actors, utilities in particular, in making decisions. While many ideas considered in this paper have been put forward in recent years, such as the need to manage intermittency of renewable resources by means of proactive forecasting, and coordination with responsive demand and storage, we introduce a possible systematic IT-enabled mechanism necessary for the actual implementation of these technologies. We point out that in order to achieve a long-term sustainable energy utilization, it is essential to provide on-line information to internalize the value of just-in-time, just-in-place, and just-in-context distributed adaptation across the entire supply chain, ranging from the smallest consumers and energy providers, through their aggregators and system coordinators. We illustrate using our model-based novel simulator, how a carefully designed multidirectional and multi-temporal information exchange could enable sustainable decision making while accounting for unique needs and capabilities of various resources and users. At the same time, information incentivizes the resources and users to contribute to system-wide sustainability objectives at value. We illustrate the dependence of such decisions-driven industry evolution on the industry rules (choice of performance objectives), as well as on the operating and planning practices for implementing the industry rules (temporal and spatial factors). Our model-based simulator could be used as a means of designing novel regulation defining rules, rights, and responsibilities regarding the type and rate of information to be exchanged in support of sustainable industry evolution.

Index Terms—Adaptive sustainability, future electric energy systems, just-in-context (JIC) services, just-in-place (JIP) services, just-in-time (JIT) services, price-responsive demand, renewable resources.

I. INTRODUCTION

This paper is intended to demonstrate the importance of seemingly hidden effects of industry rules, and operating and planning practices on the long-term industry performance. We put forward the conjecture that the very notion of sustainability is determined by the industry rules which determine how several key industry performance attributes are communicated and valued. For example, the acceptable emissions could be determined by the government rules setting total acceptable levels of emissions. They could also be determined by the energy users and producers internalizing these to their decision-making objectives. In general, there exists a major discrepancy between the two. Their congruence is critical to ensuring long-term sustainability [1], [3].

Moreover, the interdependencies of emissions objectives with other objectives such as energy cost, business goals, and very long-term investments in new energy resources are very strong. Most generally, we suggest that a preset demand for emissions introduces a distortion to the utilization and investment processes needed to ensure energy services characterized by carefully balanced other attributes [1], [2]. It is, therefore, needed to design a mechanism for adjusting the initially targeted emissions levels in response to how well the other energy provision attributes are met. The adaptation of targeted pollution levels as well as of other objectives key to the sustainable energy provision can be done interactively by the system users themselves and the system planners.

Broadly speaking, the context in which the interdependencies among multiple objectives are managed greatly affects the long-term sustainability. It is with these objectives in mind that our proposed framework introduces the notion of just-in-context (JIC) information technology (IT)-enabled functionality, in addition to more conventional just-in-time (JIT) and just-in-place (JIP) IT-enabled functionalities. JIC functionalities of an adaptive IT architecture are intended to ultimately align different performance objectives affecting the overall sustainability, as well as to align the objectives of those responsible for the system-wide performance and the system users. While these general observations have already been made in the context of other socio-ecological systems [1], there are very few sufficiently detailed models and simulators capable of quantifying potential benefits of such feedback and adaptation. Our simulator shows using a small electric energy system example that this alignment is feasible and that it would go a long way toward bringing closer the objectives of the stakeholders and the society as a whole. In particular, if one were to overlay the physical energy system with an IT-enabled system whose information and intelligence are carefully designed [4], such IT architecture would become
the main enabler and catalyst of sustainable energy system performance. This paper is an attempt to illustrate basics of such IT architecture.

In the first part of this paper in Section II, we review the industry objectives as they have evolved over time. We point out that today’s operating and planning practices consider the total generation cost as the only performance objective, while demand, emissions, delivery, and reliability are viewed as constraints. This, in turn, leads to characterizing these as externalized, and creates a disconnect of their value from the overall industry performance. We propose instead, a qualitative departure to an approach in which most of these externalized constraints are internalized as the performance objectives, and thereby become property rights, namely. Our model of the future energy industry is based on such value-based internalization of the sustainability attributes.

We further suggest in Section III, that when dealing with other types of commodities, the proposed approach would lead to a market design without requiring tight specifications of when the information is exchanged and by whom. We point out that given the unique temporal and spatial characteristics of electric energy, it is indeed critical to implement the internalization of sustainable industry objectives in concert with carefully transformed operating and planning practice rules.

In Section IV, we pose such possible implementation framework, including the underlying industry architecture, basic model-based decision tools, and information exchange specifications. Different well-understood industry organizational models become particular cases of this interactive industry organization. In Section IV-A, basic temporal and spatial characteristics unique to the electric energy industry are highlighted and used to illustrate the type of decision tools and information needed to implement this new framework. We show how the tools transform from highly coordinated single objective constrained optimization into a set of distributed carefully coordinated tools.

In Section V, we illustrate use of such decision-making tools for achieving short-term sustainable utilization of the existing and novel resources assuming today’s and transformed operating practices. Such simulator becomes a basic means for assessing the short-term performance in systems with nonconventional technologies. We show conceptually how such a simulator could be used to integrate highly diverse resources connected to a large complex electric power grid and catalyze sustainable energy provision. In particular, the key role of short-term prediction of intermittent power and electricity prices, and look-ahead dynamic scheduling tools is stressed.

In Section VI, we formalize the long-term sustainability objectives and our model-based framework in support of new sustainable investments. Here, we return to the first conjecture to illustrate the strong contextual dependence of industry performance on the industry rules (system-level performance, in particular), as well as on the short-term operating practices assumed when long-term planning is done. Perhaps the most attractive aspect of our proposed framework is its natural ability to consider effects of a large number of small-scaled technologies. The benefits of these technologies come from the economies of systems and the scope related to JIT, JIP, and JIC adaptability, as equally valid candidates as the technologies whose main advantage is brought about by their large capacity and the scale economies. The most efficient use of the existing resources and the deployment of best technologies must consider these equally. The role of aggregators in facilitating utilization of many small diverse resources is crucial.

In Section VII, we summarize the minimal transformation of today’s software tools and IT needed to implement the envisioned sustainable utilization in future energy systems. Finally, in Section VIII we recapture the subtle features of the proposed framework which we consider to be necessary for implementing sustainable energy utilization. We discuss the relation of the proposed framework to the requirements for secure energy services within an otherwise open-access interoperable environment. We point out that the information exchange structure proposed here should be considered as the interoperability standards are designed. If the standards do not lend themselves to deploying a multidirectional information exchange of the type and rate critical for JIT, JIP, and JIC adaptation, for example, this would prevent implementation of these functionalities we consider to be the key to sustainability.

II. OVERALL COMPLEXITY OF SUSTAINABLE ENERGY PROVISION

While the notion of sustainability has not been standardized, it is generally agreed that this is a long-term attribute associated with a system or process of interest. Moreover, it is also understood that for this attribute to be met, a careful balance of multiple objectives often in conflict must be set. If the balance is not made, the process will be dominated by some objectives at the expense of others, which then become hard to meet and sustain.

A sustainable energy system is one particular example of many complex socio-ecological sustainable processes [1]. Its sustainability is generally characterized by several attributes, such as:

1) ability for supply and demand to match during normal conditions (viability);
2) ability for supply and demand to match during abnormal conditions (reliability);
3) short- and long-term efficient energy utilization (efficiency);
4) low pollution (environmental sustainability);
5) impacts on technology providers and consumers (business sustainability and well being).

Energy sustainability could be viewed as a multiattribute comprising system viability, reliability, efficiency, environmental, and business sustainability attributes jointly contributing to the overall societal well-being. It is clear that these are preclusive of each other, and that much care must be taken to ensure acceptable long-term balance.

As the industry is transforming itself in response to various drivers, it is critical to take a step back and understand the contextual relations of deploying new technologies and their impact on achieving sustainable energy provision. The natural temptation is to believe that the more clean components one deploys, the more sustainable the system becomes [5]. While such clean hardware components contribute to the environmental sustainability locally [6], their contextual interdependence with other components and objectives may lead to a poor overall
reliability constraint. According to sustainability goals, the federal government has been in the process of establishing new emissions-related constraints. More coordination with the regions and states is needed.

Meeting the forecast and actual demand, ensuring that the scheduled power is delivered without creating grid congestion, as well as ensuring that the customers are unaffected during unplanned equipment outages have all been treated as constraints defined by the utilities. This approach inherently creates large system externalities. It is further believed that these are best managed because of the economies of scale by the utilities building large equipment and charging its consumers for these investments. The tariffs are based on the prescribed regulatory formulae which generally differentiate one class of customers from the others not according to their impact on the system, but, instead, based on their size, for example. In a fully regulated industry, the tariff is a pass through O&M generation cost and the capital cost charge based on the relative load peak. For all practical purposes, the process of selecting what type of generation to produce and/or build is determined according to the least cost optimization objective subject to system-wide externalities. As a result, utilities decide how much power to produce subject to the CO$_2$ fixed constraint, and schedule least-cost supply to meet forecast demand so that transmission limits are not violated. The large portion of electricity cost is a consequence of not using the most effective and least costly technologies in order to have enough reserve to supply customers when an unexpected equipment outage occurs. This has been known as the $(N-1)$ reliability constraint. According to today’s utility rules, reliability is viewed as a system constraint and not as a part of optimization criteria. Moreover, the power consumers are not active decision makers.

\begin{table}[h]
\centering
\begin{tabular}{|l|l|}
\hline
Single optimization subject to constraints & Reconciling tradeoffs \\
\hline
Schedule supply to meet given demand & Schedule supply to meet demand (both supply and demand have costs assigned) \\
\hline
Provide electricity at a predefined tariff & Provide electricity at QoS determined by the customers willingness to pay \\
\hline
Produce energy subject to a predefined CO$_2$ constraint & Produce amount of energy determined by the willingness to pay for CO$_2$ effects \\
\hline
Schedule supply and demand subject to transmission congestion & Schedule supply, demand and transmission capacity (supply, demand and transmission costs assigned) \\
\hline
Build storage to balance supply and demand & Build storage according to customers willingness to pay for being connected to a stable grid \\
\hline
Build specific type of primary energy source to meet long-term customer needs & Build specific type of energy source for well-defined long-term customer needs, including their willingness to pay for long-term service, and its attributes \\
\hline
Build new transmission lines for forecast demand & Build new transmission lines to serve customers according to their ex ante (longer-term) contracts for service \\
\hline
\end{tabular}
\caption{Examples of sustainable versus unsustainable energy provision objectives.}
\end{table}

This, in turn, leads to characterizing these as externalities and creates a disconnect between their value and the overall industry performance. Moreover, given today’s horizontal industry organization, the objectives are defined by the utility and periodically submitted to the states in which they are located for approval. In general, there has not been much regional coordination for economic reasons. As new societal objectives have begun to emerge driven by the overall energy sustainability goals, the federal government has been in the process of system sustainability. The components may be unacceptably costly as seen by the consumers, or they may not be able to recover the investment made for their deployment, or they may create highly variable supply demand imbalance which must be managed by other not so clean technologies, and so on.

The combinatorial complexity of providing sustainable energy is simply overwhelming. Because of these multidimensional features of complexity, it would be hard to achieve desired levels of sustainability by deploying only very few specific technologies. In what follows, we describe how are these general concerns even more complex in a system like an electric energy system.

In this section, we briefly summarize the contextual changes in the industry brought about by both organizational changes and the technological advances. We contrast today’s industry operating and planning objectives with the evolving ones next. Illustrations of these qualitatively different objectives are shown in Fig. 1.

A. Today’s Industry Paradigm: Single Objective Subject to Many Constraints

The main objective of today’s industry, shown in the left side of Fig. 1, is its total generation cost minimization. Operating rules and current software in control centers have evolved around this objective for given system design. Similarly, the new investments are made primarily with the capital cost in mind, subject to all else being an explicit constraint. An exception to this rule in the U.S. industry has been practiced by some utilities following the tradeoff analysis of capital and operating costs. In particular, demand, emissions, delivery, and reliability are viewed as constraints. This, in turn, leads to characterizing these as externalities and creates a disconnect between their value and the overall industry performance. Moreover, given today’s horizontal industry organization, the objectives are defined by the utility and periodically submitted to the states in which they are located for approval. In general, there has not been much regional coordination for economic reasons. As new societal objectives have begun to emerge driven by the overall energy sustainability goals, the federal government has been in the process of establishing new emissions-related constraints. More coordination with the regions and states is needed.

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Shown in the right column of Fig. 1 is a qualitative departure from today’s industry practice to an approach in which most of the system-constraints-related externalities are internalized as the performance objectives, namely, they become property rights. Our model of future energy industry is based on such value-based internalization of these attributes. Moreover, it appears that such internalization is impossible to carry out once for good off-line by the government and/or utilities because these entities would never be able to differentiate among the highly diverse temporal, spatial, and contextual needs and capabilities of very many small distributed energy resources (DERs). Instead, we propose that the internalization be done by the energy users and providers, and that this information be communicated to the aggregators and system coordinators. We will show later in this paper how by taking such an approach the very demand for emissions and the resulting energy cost are obtained as a result of clearing specifications made by the system users themselves who have internalized the negative value of emissions, congestion, and reliability. Consequently, the demands for emissions, delivery, and reliability are no longer a preassigned fixed quantity. They are, instead, a result of bottom-up specifications of values, needs, and capabilities by all to the participating entities.
III. CONTEXTUAL, TEMPORAL, AND SPATIAL CHALLENGES TO MAKING ELECTRIC ENERGY INDUSTRY SUSTAINABLE

It is important to appreciate fundamental differences between the distributed value-based supply demand balancing of conventional commodities from the problem of providing sustainable electric power grid-enabled energy. The main differences are due to the lack of large-scale cost-effective storage, and the complexity of grid power delivery during normal conditions (demand is close to forecast and no unplanned equipment outages) and during abnormal conditions. The industry rules and practices have been developed over many years to ensure that as consumers are supplied there are no congestion nor reliability problems, for example. The industry practices do not differentiate between various levels of reliability; instead, all consumers within single utilities are served according to the same reliability constraints, such as no more than one day of interruptions in 10 years. It is well-known that the cost of these externalities is quite high, since the investment rules are such that there must be sufficient reserve to serve the peak hour even during the largest equipment outage. This is the so-called \( N - 1 \) industry reliability rule. The cumulative costs of maintaining over 10\% generation reserve, under 30\% of thermal transmission capacity average utilization, and the inability to dispatch the least cost power plants, for example, are quite high. Today’s industry rules do not rely on corrective actions nor timely adaptation in response to system conditions.

In our proposed framework, we suggest that much could be gained by beginning to rely on JIT and JIP actions, in particular. It is shown in what follows that the value of prediction is high, and that a dynamic look-ahead decision making based on the predicted information is generally much more sustainable than a strictly static decision making. This is particularly the case because most of the resources have their internal dynamics which prevents them from responding instantaneously. By dispatching these resources in a look-ahead manner, it becomes possible to have average contribution of even very slow resources more valuable than when their dispatch is static. The illustrations of this dependence of system performance on the information available and the type of decision-making tools needed are given in the later sections of this paper.

Moreover, in order to provide right incentives to the distributed decision makers, it is important to have their information on the value of the outside service internalized and communicated to the coordinating authorities. Without this information it is hard to differentiate among various stakeholders according to their needs, capabilities, and willingness to pay. If this is not done, it becomes practically impossible to induce adaptive behavior which would contribute to the system-wide objectives at value.

The degree of differentiation and aggregation will generally determine how well the overall industry performs. Extreme decentralization is impossible to manage by the coordinators of network power grids whose complexity has become huge due to sheer number of consumers and producers and their heterogeneity [12]. It would be practically unthinkable to manage every single user as a separate entity. On the other hand, entirely aggregated, fully coordinated, management is hard to implement due to a lack of data about all the system users and poor understanding of their correlations. Moreover, the results of entirely centralized management would not provide differentiated signals about the effects of specific users on the system-wide objectives. Therefore, it becomes practically impossible to provide sufficiently accurate incentives for adaptation so that system-wide objectives are met at value.

IV. POSSIBLE IT-ENABLED IMPLEMENTATION FRAMEWORK IN SUPPORT OF SUSTAINABLE ENERGY INDUSTRY

Given the characteristics unique to the electric energy systems, we introduce here a possible IT-enabled implementation framework in support of the sustainable energy industry. The main intent is to ultimately internalize all hard constraints such as reliability by relying on JIT and JIP interactive information exchange between the individual consumers, portfolio of consumers and DERs, large producers and consumers, on one side, and the aggregators and system operators as coordinators, on the other side. The amount of reserve required is no longer a predefined quantity as it was in the old industry. Instead, specifications by the end users regarding the reliability of service during the abnormal conditions and the willingness to pay for this service would lead to internalizing the value of differentiated reliability and making the coordination part of determining the actual price for reliability and the level of reliability. Different variations are possible here, depending on how the uncertainties are specified. For example, if the demand has a time-of-use profile and the willingness to pay for some minimal service during major system interruptions, the resulting system performance would be different than if the load responds solely to the near-real-time price signal. Here again, the value of prediction and look-ahead dispatch is key to a more stable, less costly, and cleaner reliable energy provision at value. As the cost of reliable provision increases, the system users adjust by internalizing this predicted cost and provide requests for reliable service which is lower than when the price of reliability was lower.

Due to a lack of space, we omit a discussion concerning the value of internalizing congestion. Basically, if the locational marginal prices (LMPs) are higher, the system users internalize this signal by deciding how much delivery of power to request in order to balance the tradeoff between the benefits from electricity they need and the cost of congestion. If all system users, producers, and consumers do the same, it can be shown that this process of internalizing congestion converges to the same system-wide optimum. Important to observe is the fact that although system-wide performance is near identical, the value of delivery to different system users is different and more aligned with their specifications than when the information about the willingness to pay for congestion was not provided to the system coordinator. This information can only be provided using multidirectional information exchange [17].

A. Basic Information Flow Required for Achieving Sustainable Energy Provision

There have been several proposals of IT-enabled architectures in support of future electric energy systems which resemble our proposed framework [8], [9]. This paper is the first to our knowledge which puts forward model-based information exchange and embedded decision-making algorithms capable of supporting a sustainable energy provision. An interactive model across the entire supply chain with all groups of decision makers
and the coordinating entities exchanging information could be posed as the problem of resource allocation under uncertainties [10]. There are several ways of organizing this problem into sub-problems depending on how one defines the energy attributes. The most effective architecture would depend on the approach taken. In what follows, we contrast two qualitatively different approaches.

To start with, the information flow architecture is multidimensional across time, space, and industry participants. Under our proposed framework, a benchmark sustainable energy provision is obtained by co-optimizing several key attributes subject to very few constraints, if any. A completely unconstrained multi-objective optimization would end up with a solution in which power quantities dispatched and built are such that the cumulative short-run and long-run marginal system costs of various objectives are the same. This would, in turn, result in corresponding energy quantities. This result, however, is under the assumption that no technological constraints exist (capacity of different technologies, rate of response, no delivery constraints) and, that, notably, there are no uncertainties of any type. Even before one attempts to design such solution, there is a question whether this is indeed what should be meant by sustainable energy provision. It is perhaps more realistic to carry this design given the best possible estimates of very long-term energy resource availability as well as the best possible scientific estimates of what would be acceptable total pollution of various types over the decision time horizon. The decision process should consider such constraints, and explore the potential of all technologies likely to be available.\(^1\) We point out that this solution would perhaps provide a more realistic problem posing. In practice, it would be almost impossible to arrive at this result for variety of reasons, as discussed earlier in this paper. Moreover, the solution would not allow for an interactive alignment of values brought about by such design to the energy system participants and to the centralized optimizer. Needless to say that the effects of long-term uncertainties and the risks associated with these uncertainties are the overwhelming determinant in what ultimately happens [1].

It is illustrated in this paper that for given industry objectives the long-term industry performance greatly depends on the actual implementation. The design problem could then be viewed as the one of embedding the right IT support and decision-making tools within the physical energy systems in order to best manage uncertainties and to align in the best possible way the objectives of all members of this energy system. The conjecture is that this approach would result in as sustainable energy systems as possible, while enabling choice.

**B. IT Architecture in Support of Energy as a Multiattribute Product**

One possible way is to consider energy as a multiproduct in which energy, energy delivery, and energy pollution are all products contributing to the energy service itself. This would lead to multilateral exchanges of information regarding energy needs and supply and the willingness to pay for these, independent from the other attributes.

1) **IT Architecture for Energy Supply Demand Arrangements:** The process of settling at the energy choice which reflects the value to the suppliers and consumers subject to maximization of social welfare would require exchange of supply and demand functions, both short- and long-term functions. It is known that the formulation of this problem as a dual optimization problem requires information to be sent by the coordinating entity about the Lagrangian coefficients (energy prices) \(\lambda_{\text{coal}}\) on one side, as well as information to be sent by the suppliers and consumers about their energy supply and demand functions \(b_{\text{coal}}(t)\) for example, as shown in Figs. 2 and 3. Each supplier and consumer internalizes the value of energy for the given expected energy price (by solving his own primal distributed problem). The coordinator collects all bid functions, and coordinates the best combination of resources and clears the price by solving the dual system level problem.\(^2\)

However, the candidate energy providers and consumers can only use physically implementable and environmentally acceptable solutions. This requirement then gives system users an opportunity to select either an electrically closer energy provider and not pay for delivery, or pay for delivery and obtain energy from a further away more attractive energy provider. Similarly, system users could either not pollute or have to pay for pollution they are creating. Implementing this decision-making process calls for two other IT architectures, again not necessarily of unique design.

2) **IT Architecture for Energy Delivery Arrangements:** There has been some work related to the locational marginal pricing in the spot electricity markets which points in the direction of either a bundled energy and delivery design or unbundled energy and delivery processes [17]. The demand functions for de-

\(^{1}\)Such problem formulation would perhaps miss the effects of some breakthrough technologies unknown at the time the design is done, but the probability of having these effects is not extremely high given the complexity of their development and integration in the existing system.

\(^{2}\)Only the energy portion of the product can also be managed by the suppliers and consumers exchanging multilaterally their bid curves without having a system-level coordinator. Under some relatively mild assumptions, the two equilibrium solutions can be shown to be the same. However, the time required for information discovery may be prohibitive in the actual dispatch of electricity. This process results in candidate physical energy exchanges.
livery $E_{ij}^k \lambda(t)$ are created by the system users, often a pair of a producer located at node $i$ in the network and a consumer located at node $j$ in the network, needing to implement their energy supply-demand arrangements. The delivery supplier is a transmission system owner and/or coordinator.\textsuperscript{3} It can be shown by posing the energy delivery provision problem as a dual optimization problem with respect to the system-wide performance objective that the information process by which those needing delivery communicate their specifications concerning the needs for delivery and willingness to pay for it, as well as the delivery provider communicating delivery available and price at which it is willing to sell it, results in locational delivery prices the process converges to the system-wide optimum obtainable by solving the original primal problem of transmission provision $\lambda(t)$.

Nevertheless, because the delivery performance function is generally not decomposable, the delivery problem cannot be solved without any information about the network. This information can be either in terms of physical congestion constraints given to the system users for internalizing them when settling on energy supply demand arrangements, or in terms of locational prices for delivery. For the preselected delivery objective, the system-wide performance (cost of delivery) is the same, but the values brought about by the solution are different in the two cases.\textsuperscript{4} Notably, the system-wide result depends on the preagreed system-wide performance objective. If the delivery provider’s objective is to maximize its own system-wide revenue from delivering energy, the solution will be very different than when the objective is to minimize social welfare of the system users.

3) IT Architecture for Managing Environmental Impact: At least in principle, since both environment and network are ultimately limited resources affected by all system users and the coordinating entities, it is possible to introduce an IT architecture for exchanging specifications concerning the clean supply and demand capabilities and needs, as well as the willingness to be paid and pay for $E_{wind}(t)$ and $E_{coal}(t)$, respectively. Fundamentally, this is the same as the separable energy delivery provision process described above. All of the issues highlighted regarding delivery are conceptually the same. This points to the major issue concerning the criticality of proposed system objectives in support of sustainable environmental impact. Possible objectives range from specifying total annual polluting emissions and constant emissions cost (tax).

The information flow sketched in Fig. 2 is intended to support alignment of different performance objectives associated with specific industry layers, ranging across the entire supply chain. This functionality is called JIT functionality. The same information flow is also intended to support alignment of different performance objectives associated with different time horizons. This functionality is known as JIT functionality. The same information flow will support sustainable JIP energy delivery functionality. Finally, the information flow is also intended to support alignment of different stakeholders across an otherwise very complex system. An illustration of this example with an aggregated energy service provider is shown in Fig. 3. The outcomes of an otherwise identical system with and without the presence of aggregators can also be interesting. While the immediate reaction is that they are, as a rule, contributing to suboptimality, it is suggested in [1] that larger groups of decision makers are generally more effective than the individual users in contributing to sustainability. The impact of aggregation on electric energy systems needs to be studied in the future.

C. IT Architecture in Support of Energy as a Single Product

In a similar way, one could envision an IT architecture which supports bundled energy, delivery, and environmental objectives. The pros and cons for the two need to be studied in the future. It is clear, however, that an entirely single product energy provision would fall short of reflecting diverse needs and capabilities of energy users and providers. On the other hand, this architecture avoids the duality gaps created by the decomposition of energy provision into multiproducts. A schematic representation of such IT architecture is shown in Fig. 4. Here bundled bids for energy service which internalize at their level value of delivery and environment $E_{Bundled}(t)$ are exchanged with the system coordinator and a single bundled price of electricity is sent back as $E_{Bundled}(t)$.

Major studies are needed to assess comparison of these two qualitatively different approaches to providing future energy services.

D. Key Role of Aggregators

The actual implementation of sustainable energy services is possibly best done by the dedicated service providers whose main purpose would be to correlate often very diverse needs of individual system users, and to serve as mediators between the large number of small actors and the rest of the system. Although the most optimal utilization is generally achievable by managing the entire system in a coordinated way, it is becoming increasingly clear that an effective internalization of many

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\textsuperscript{3}Much debate has taken place concerning the differences between the two. It is known that under certain conditions the two result in the same system-wide optimum but generally different values to the system users, namely their profits from selling energy and benefits from purchasing energy.

\textsuperscript{4}This is true except for the case of when both performance objective and supply and demand functions are linear.
complex factors affecting sustainable services is impossible to be carried out once for good off-line by the government and/or utilities. This is because these entities would never be able to differentiate highly diverse temporal, spatial, and contextual needs and capabilities of very many small actors. Instead, the internalization is best done by the energy users and providers in an interactive way with their aggregators. The very demand for emissions and the resulting energy cost become a result of clearing such internalization-based specifications of the system users by the aggregators. Consequently, the demand for emissions, delivery, and reliability is no longer a preassigned fixed quantity. It is, instead, a result of bottom-up specifications of values, needs, and capabilities by all to the coordinating entities. This, in turn, ultimately contributes to the alignment of centralized and distributed objectives, as well as to a sustainable management of multiple performance objectives. In simple terms, if the cost of energy provision begins to rise considerably, the system users would respond to it by consuming less and, consequently, stabilize potentially skyrocketing cost. Such self-adaptation of multiple objectives through an interactive information exchange is referred to in this paper as the sustainable system management.

We illustrate next our second conjecture which states that, given the same industry rules, the actual implementation of the operating and planning practices will greatly affect the major industry attributes, such as the long-term capital cost of investments, cumulative short-term utilization efficiency, and their tradeoffs, in particular. Also, key factors, such as predictability of system dynamics, number of users, knowledge of the system, and collective choice rules, will affect the long-term outcomes in a major way. We illustrate, for example, that the integration of highly variable clean resources without changing operating and planning practices is not sustainable with regard to energy cost and the long-term resource adequacy. Most of the long-term projections of sustainability trends do not account for these technical aspects unique to the electric energy processing. In Section V, we illustrate the major role of JIT and JIP functionalities which must be enabled by the IT architectures in order to make the most out of the available resources.

V. SIMULATOR FOR ILLUSTRATING DEPENDENCE OF SHORT-TERM PERFORMANCE ON THE IMPLEMENTATION MECHANISM

In this section, we illustrate through an example the implementation of short-term efficient operation towards a more sustainable electric energy system. In particular, given the high variability and heterogeneity of many new energy resources (e.g., plug-in hybrid electric vehicles (PHEVs), wind and photovoltaic power generation, pumped hydro generation), the value of look-ahead dispatch and price-responsive demand [7] is emphasized.

Fig. 5 shows a three-bus legacy power system comprising two fossil-fuel generators and one inelastic demand. Several new components are added to the legacy system denoted by the green dotted line. Depending on the operating practices, potential economic and environmental savings from adding these new resources will be quite different. To illustrate this, several scenarios are simulated.

1) Legacy system without renewable energy resources
This represents the conventional operating practices in legacy power systems. In order to supply the expected load at each hour, single objective cost minimization takes place at the control center. The result is economic dispatch.

2) New system with static dispatch and inelastic demand
The added renewable energy resources such as wind and photovoltaic have high intertemporal variability and time-varying available outputs. Current static dispatch practices typically do not differentiate explicitly the rate of response in the optimization procedure. Therefore, in order to counteract the highly variable outputs from the renewable generation, fast responsive conventional generators (e.g., the natural gas unit) are needed [11]. In such a scenario, the slow units are dispatched every hour ahead, whereas the fast units are dispatched at more refined time-interval (e.g., 10 min ahead).

3) New system with look-ahead dispatch and inelastic demand
In contrast to static dispatch in Scenario 2, a look-ahead dispatch is simulated which takes into account a) the prediction of variable resources, and b) the rate of response of different types of generators [13]. In this scenario, the
predicted available renewable generation and the ramping rates of all the units are explicitly modeled as the intertemporal constraints.

4) **New system with distributed, interactive dispatch and elastic demand**

With more and more dispersed and heterogenous energy resources, a distributed interactive dispatch of elastic demand is simulated in Scenario 4. Distributed decision makers (e.g., generators, elastic demands, and PHEVs) internalize their own performance multiobjectives based on the projected price signal obtained from the system operator [14]. The internalized decision-making differentiable environmental preferences, physical intertemporal constraints, and predicted available outputs. The outcome of the internalized decision-making process are the demand or supply functions, which are collected by the system operator. These bids are used to select bids according to the system-wide performance objective, such as social welfare. Fig. 6 shows four qualitatively different supply/demand curves, namely, the generator supply bid, the inelastic demand curve (fixed demand), the elastic demand curve (price adaptive load), and the PHEV supply bid under the discharging mode. These bidding curves take into account the internalized preferences and constraints. Thus when the system operator clears the market, the results are physically implementable.

**A. Comparison Results**

Several numerical results for the four scenarios are discussed next. Fig. 7 shows the coal and natural gas power generation under the four different scenarios. With no renewable energy resources, the natural gas and coal units are the only two generators to supply the inelastic demand. With the added wind and photovoltaic power generation, the natural gas and coal power generation is reduced. However, depending on the use of information in the operation practices, the environmental and economic benefits could be quite different. As illustrated by the plots drawn in black and purple, the addition of renewable energy resources reduces the generation from fossil fuel-based units. However, the variability of outputs of the fast unit (natural gas) is significantly increased. If the dispatch is look-ahead rather than static dispatch, then the output of less expensive unit (coal) will increase by about 2%. If the price-responsive demand and distributed decision making are introduced as in Scenario 4, then the total generation of both coal and natural gas units get reduced significantly.

Fig. 8 shows the total system demand and the renewable power output under several different scenarios. Given the variable outputs from wind and photovoltaic generators, the elastic demand self-adjusts to the intertemporal variation, therefore reducing the burden of fast responsive fossil fuel generation unit (natural gas). In this figure, we can also see that given a different level of PHEV penetration, the total system demand will be varying.

Figs. 9 and 10 compare the total generation cost and total CO₂ emission under the four different scenarios in a typical day. It can be seen that introducing renewable energy without
change of the operating practice will reduce only a modest amount of total generation cost and emission (generation cost reduced by 20% and emission reduced by 4%). However, by introducing look-ahead dispatch with price-responsive demands, the potential gain with the same system composition is much higher (generation cost reduced by 53% and emission reduced by 9%).

In summary, an IT-enabled distributed interactive operation framework is simulated in this section. In comparison of the centralized static dispatch with inelastic demand, a distributed interactive operation scheme with price-responsive demands could lead to a more cost-effective and environmentally friendly utilization of variable energy resources. The effect of the implementation method used is highlighted.

VI. SIMULATOR FOR ILLUSTRATING DEPENDENCE OF LONG-TERM PERFORMANCE ON THE IMPLEMENTATION MECHANISM

A. Planning

In addition to designing an IT-enabled mechanism for sustainable short-term utilization of the existing energy resources, it is essential to facilitate evolution of a sustainable long-term electric energy industry. This must be done by selecting the most effective investments based on the availability of both mature conventional resources and many recently introduced technologies. The candidate technologies are qualitatively different in many ways, and it is practically impossible to mandate their deployment by continuing today’s planning practices. There exists, therefore, a serious need for designing a new planning framework in support of deploying sustainable technologies in which the necessary data would be transparent and the necessary information would be exchanged interactively among those proposing new investments and the system planners.

Much the same way as we have proposed here an interactive short-term dispatch of available resources in order to reconcile distributed subobjectives of many decision makers, with the system-wide sustainability objectives, we envision a similar IT-enabled mechanism for proposing and selecting new investments [15]. Such an interactive planning framework (IPF) is posed as a distributed decision-making problem which accounts for tradeoffs between cumulative operational effects and cost of new investments. However, instead of assuming long-term demand needs by the system planners as it is currently done, it is critical to base the new investments on the information by the load serving entities (utilities, aggregators) about their long-term future energy needs, and the willingness to pay for such energy provision. Instead of making the least-cost decisions for uniform reliable service, it is necessary to switch to a peak-load pricing-based approach in which customers’ short- and long-term demand specifications are considered at the planning level [16]. An IT-enabled mechanism in which information is provided by the potential investors in generation, by those needing energy, and the system planners selecting actual investments, forms the basis for an interactive planning framework, as recently proposed in [15]. Such a mechanism would enable the power plant owners to create their long-term bids to invest in new capacity for the anticipated prices over the long-time planning horizons, according to the well understood needs specified by the energy users. Moreover, different groups of energy users could specify different priorities of future service and the willingness to pay for it. The selection of the best investments by the system planners to meet nonuniform requirements by the energy users would amount to implementing differentiated sustainable energy provision at value. The bids for building a new generation $\text{gen}_{\text{new}}\left(t\right)$ are communicated to the system-wide planning authority, at the same time as the needs by the users are specified. These long-term bids are cleared so that the system-wide long-term sustainability criteria are met. This method could be shown by simulating the proposed IPF to avoid typical boom and bust investment cycles. Moreover, much the same way as for implementing short-term sustainable services, an effective implementation of sustainable new resources requires information about the estimated future long-term prices be given by the system planner to all. A two-stage auction supporting information exchange between the system users and the planner is key to distributing investment risks over all participants at value, and to allining their long-term objectives with the system-level objectives. We view the proposed planning framework as the necessary paradigm for planning in the changing industry where choice must be reconciled with the societal public objectives.

The long-term outcomes will be different when the energy is considered to be a multi- or single-product. Many open questions concerning the needs for new investments can be studied by simulating such an interactive planning framework. In particular, the dependence of the evolving generation mix on the choice of the long-term system-wide performance objectives could be studied; this is illustrated next. Notably, the effectiveness of new investments in both new and old technologies will depend on the type of information exchanged, the time horizon.

![Fig. 9. Total generation cost under the four scenarios in a typical day.](image9.png)

![Fig. 10. Total CO₂ emission under the four scenarios in a typical day.](image10.png)
over which it is exchanged, and if the information is binding or not. Designing regulation for necessary information exchange could be pursued using the interactive planning framework here. Given the target system-wide objectives, it is possible to select the right IT design so that such objectives are implemented while enabling choice for long-term investments.

B. Least-Cost Interactive Planning Framework

We illustrate here the dependence of planning outcomes on the candidate technologies considered and their short-term utilization implementation mechanisms. We show that the scenarios described in Section V will result in different investment plans given the same system-wide long-term performance objective. To start with, we illustrate this by selecting the long-term minimum-generation cost as the planning criteria. One example of this is shown in Figs. 11 and 12. For Scenario 1, a long-term expansion planning approach accounts for the operating costs, capital investments, and physical dispatch limits of generators. This is a conventional minimum-cost planning approach (blue color in the figures—C+NG). For Scenario 2, there are two planning options. The first option (magenta color in the figures—C+NG+W+S) is the traditional long-run expansion planning with estimated wind and solar dispatch. The second option (red color in the figures—C+NG+W+S—Static dispatch) is minimum-cost planning where physical generator limits are replaced with bidding functions $b^\text{gen}_{\text{type}}(t)$. These static dispatch bids give generators upper and lower power limits and operating costs for each hour during planning period. Scenario 2 in comparison with Scenario 1 will have must-run time for a gas power plant unit as it was explained in Section V. For Scenario 3, the optimal plan (green color in the figures—C+NG+W+S—A look-ahead dispatch) is calculated by using the bidding functions $b^\text{gen}_{\text{type}}(t)$ that are determined by a look-ahead dispatch instead of the static dispatch.

With no renewable energy resources, the natural gas and coal units are the only two types of generation to supply the inelastic demand (C+NG). With the added wind and photovoltaic power generation (C+NG+W+S), the coal power and natural gas required capacity is reduced. However, the natural gas output is increased during hours with high renewable sources volatility. These two examples assume physical power plant limits. If a static dispatch is used instead of the physical limits (C+NG+W+S—Static dispatch), the natural gas power plant will be used even during off-peak hours when renewable sources volatility is high because the coal power plant has a cheap operating cost, but it cannot provide load following. The best scenario is obtained when a look-ahead dispatch is used for short-run operation (C+NG+W+S—a look-ahead dispatch). In this case, the required capacity is reduced.

C. Peak-Load Pricing Approach to Interactive Planning

When elastic demand is included into the planning process (Scenario 4 in Section V), the minimum-cost planning method becomes a distributed interactive peak load pricing-based planning method. This approach accounts for tradeoffs between cumulative operational effects and cost of new investments. Both supply and demand will be represented by long-run bidding curves: $b^\text{long}_{\text{gen}}(t)$ and $b^\text{long}_{\text{dem}}(t)$, respectively.

1) Peak-Load Pricing Approach by the Technology Owners: A long run bid function $b^\text{long}_{\text{gen}}(t)$ is calculated as a part of IPF. Generator owners will decide how they will utilize existing generation capacities and if they want to invest in a new plant based on expected $\lambda^\text{long}_{\text{EIS}}$ during a planning horizon. If the expansion plan is based only on the forecasted load (Fig. 13), the uncertainty is high and a generator owner will not be able to
recover its capital investments. The expected $X_{\text{HH}_i}$ should reduce risk associated with the new capital investments. It is clear that the future is uncertain but obtaining the right information may reduce risk. Power suppliers run maximum profit optimization based on assumed $X_{\text{HH}_i}$, operating costs or $h_{\text{gen} \text{ type}}(t)$ and capacity payments. They design $h_{\text{gen} \text{ type}}(t)$ based on the sum of total annual energy cost and annualized capital investment for different installed power. As an illustration, the first year $h_{\text{Coal}}^{\text{long}}(1)$ and $h_{\text{NG}}^{\text{long}}(1)$ are shown in Fig. 14.

2) Peak-Load Pricing Approach by the Long-Term Elastic Demand: In order to determine how much demand is available for a limited capacity, or how much demand can be utilized to have a more sustainable energy system, it is crucial to better understand the value of additional capacity to demand. In a short-term optimization by the system and the end-users, there has been work done to capture individual residential end-users’ value or willingness-to-pay of electric energy by modeling optimal energy used for space conditioning of an end-user with respect to hourly varying electricity price [7]. This work calculates each end-user’s demand function by relating the optimal electric energy usage with respect to the hourly price that they pay, in order to optimize their own preference on energy consumption.

In a similar way, we capture the effect of long-term investment on energy cost savings of end-users with respect to their peak energy usage. We assume that, by investing in insulation of an end-user’s residential building, she can reduce the energy cost and the peak demand over a year. As an illustration, we optimize this objective over the 10-year period, similar to creating generation planning offers. We set different levels of investment that result in different peak demand required. The base investment cost is assumed as $2500 per household, and an additional cost of $100 per household was set to take into account an increment of the investment level. The number of the end-users are adjusted so that it is in the same order of the capacity on the supply side.

An accurate model of the relationship between investment cost and the energy consumption needs more rigorous experiments. However, for the sake of observing the relationship between the demand and supply bids in the long run, we perform least square estimation on the data pairs of the total cost including the investment cost and the cumulative energy cost, and the corresponding peak demand quantity. The demand quantity by investing a certain amount in insulation and the resulting peak demand were calculated based on the short-term (hourly interval) optimization of end-users’ energy usage, with respect to the given hourly energy rates.

The resulting demand function or marginal utility function is shown in Fig. 14. As expected, higher investment cost yields lower peak demand required, since the households have larger insulation and, therefore, consume less energy in that case. By plotting the marginal utility function alongside with the marginal supply function, we also observe the optimal point where the marginal utility and cost intersect. This implies that an optimal technology to install on the existing system can be chosen by studying the demand-side tradeoff between the total cost including the energy cost and the investment cost, and the resulting peak capacity required.

3) Discussion: An interesting observation from our particular simulation result is that the optimal cost lies between the different marginal (investment + operating) costs of coal and natural gas plants. If we choose to have additional coal generation, then at the marginal cost of coal, demand is bound to exceed the maximum capacity of the new coal plant, according to the marginal utility function. However, on the other hand, if the natural gas plant is also chosen to be built, then at the marginal cost of the natural gas plant, demand will not be willing to pay for that high cost, which can also be observed from the utility function. Therefore, the solution should be adjusting the demand by modifying the value of the demand-side’s investment and energy cost. For example, by subsidizing the insulation cost of the demand, the marginal utility function can be lowered so that the optimal cost where supply meets demand lies exactly on the marginal cost of coal. Or the short-run energy rate can be adjusted so that the investment in insulation
takes a higher value (i.e., the end-users obtain more energy cost savings), resulting in the steeper slope of the demand function.

In any case, it is important to decide the long-run monetary agreement between supply and demand, in order to have the right technology installed (or not). This agreement can be well captured by examining the values of investment and operation (on the supply side) or consumption (on the demand side) with respect to the different levels of additional capacity, which was shown in Fig. 14.

Another important point from this proof of concept is that long-run decision making should also fully account for the effects of the cumulative short-run costs and values of supply and demand. On the demand side, for example, the value of investing in house insulation is compensated by the savings in short-term energy costs. The same logic applies for the investment in a new plant as well. In other words, the correlation between the cost/value of the long-run investment and the short-run operation/consumption should be recognized in the long-run decision making.

We point out that our proposed interactive framework lends itself well to both regulated and restructured industry. The information exchange about the needs and capabilities as well as about the users’ willingness to pay for different candidate technologies is fundamentally essential for sustainable operations and investment, independent of the industry organization.

VII. NEEDS FOR NEXT-GENERATION SOFTWARE TOOLS FOR IMPLEMENTING SUSTAINABLE ENERGY UTILIZATION

Our proposed framework is based on the premise that decisions unique to specific technologies are internalized to the distributed system users and/or groups of users. It has been illustrated throughout this paper that dynamic look-ahead based on predicted information is essential to efficient just-in-time utilization of resources. This calls for novel distributed decision-making tools to be embedded within the system users and/or groups of users. However, we have shown that once this is done, it is no longer critical to modify the existing static security constrained economic dispatch. Further work is needed to assess potential suboptimality caused by not performing extremely complex dynamic look-ahead optimization by the system operators. Based on studies up to date, it appears that this is not significant. Consequently, the first implementation of the proposed framework would be feasible without requiring major software developments. The gains would come from embedding complex decision making within the distributed users and complementing this by means of active on-line information exchange within the industry and across time for adaptation.

VIII. CONCLUDING REMARKS AND OPEN QUESTIONS

The contextual notion of sustainability is directly determined by how the industry objectives are defined and implemented. At present there exists a disconnect between the overall societal expectations and drivers of sustainability, on one side, and the current operating and planning industry practices, on the other side. Theoretically speaking, given sustainability objectives, the practices become a means of implementing the objectives. Viewed from the engineering design point of view, this means that the industry practices should be based on most effective methods for implementing the sustainability objectives. Any candidate technology can be evaluated with respect to the performance metrics of interest by those who require its use. In this paper, we briefly discussed these types of performance criteria and explained how our proposed framework could be used to quantify the effect of candidate technologies on these performance criteria for any given system. Also, to start with, we recognize that assessing tradeoff performance when more than one performance criteria is of interest is fundamental to what one may consider broadly by sustainability. This has long been recognized in the electric power industry. Quantifying the tradeoffs across several types of performance criteria and defining frontier curves may become quite important in the future as one attempts to understand the interdependencies across technical, economic, and environmental performance criteria.

Moreover, because of the unique properties of electric energy management, we stress that there exists a real need to revisit the operating and planning objectives of today’s industry in order to demonstrate the potential shortcomings and opportunities of any existing and new technology. While most efforts are on assessing the impact of candidate hardware technologies, ranging from nuclear through very small DERs, it is important to highlight the key role of IT and software, most generally, in enabling their sustainable short- and long-term utilization. We made an attempt in this paper to explain that transforming data into the most useful information for coordinating new hardware utilization within the existing system is key to managing highly variable small resources in a sustainable way.

Contextually speaking, the type of information which should be exchanged depends on the performance objectives set, and, vice versa, how effectively the industry performance is met critically depends on having the key information when decisions are made. Depending on the time horizon of interest, the implementation may be either with the human in the loop or fully automated. Not having well-defined performance objectives could create major confusion in an industry which requires near instantaneous supply and demand power balance. Reconciling highly variable resources with this requirement leads to the need for JIT, JIP, and JIC functionalities. Illustrative examples are given to show that these functionalities may catalyze the enhanced sustainability beyond what is often assumed. In this paper, for the first time, we related the type of information which is necessary to exchange to the objectives of sustainability. We suggest that our proposed IT-enabled framework could be embedded into the actual physical energy systems and be relied on to help align otherwise very diverse objectives at value.

This paper only provides a starting framework for designing model-based IT-architectures for predictable performance. The examples provided are for illustration purposes. Much work remains to be done concerning the actual experiments with such architectures, and projecting at least order of magnitude effects of IT-enabled architecture embedded within a physical energy system. The boundaries between economies of scale-induced benefits, economies of systems and scope, as well as effects on behavioral changes by the system users and coordinators must be studied. It is plausible that for the energy provision to become long-term, sustainable IT-enabled architectures would be
critical for aligning federal objectives with the objectives of regions, states, utilities, and energy users and providers.

REFERENCES


Marija D. Ilić (M’80–SM’86–F’99) is currently a Professor at Carnegie Mellon University, Pittsburgh, PA, with a joint appointment in the Electrical and Computer Engineering and Engineering and Public Policy Departments. She is also the Honorary Chaired Professor for Control of Future Electricity Network Operations at Delft University of Technology in Delft, The Netherlands. She has 30 years of experience in teaching and research in the area of electrical power system modeling and control. Her main interest is in the systems aspects of operations, planning, and economics of the electric power industry. Most recently she became the Director of the Electric Energy Systems Group at Carnegie Mellon University; the group does extensive research on mathematical modeling, analysis, and decision-making algorithms for the future energy systems. She is leading the quest for transforming today’s electric power grid into an enabler of efficient, reliable, secure, and sustainable integration of many novel energy resources. She has coauthored several books in her field of interest.

Jhi-Young Joo (S’07) received the B.Eng. and M.Eng. degrees from the School of Electrical and Computer Engineering, Seoul National University, Seoul, South Korea, in 2005 and 2007, respectively. She is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA.

Le Xie (S’05–M’10) received the B.E. degree in electrical engineering from Tsinghua University, Beijing, China, the M.Sc. degree in engineering sciences from Harvard University, in June 2005, and the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University, Pittsburgh, PA, in December 2009.

He is an Assistant Professor in the Department of Electrical and Computer Engineering at Texas A&M University, College Station. His industry experience includes an internship (June 2006–August 2006) at ISO-New England and an internship at Edison Mission Energy Marketing and Trading (June 2007–August 2007). His research interests include modeling and control of large-scale complex systems, smart grid application with renewable energy resources, and electricity markets.

Marija Prica (S’05) received the B.S. and M.Sc. degrees in power engineering from the Faculty of Technical Sciences, Novi Sad, Republic of Serbia, in 2000 and 2006, respectively. She is currently working toward the Ph.D. degree at Carnegie Mellon University, Pittsburgh, PA.

She was a teaching and research assistant at the Faculty of Technical Sciences, Novi Sad, and a part-time employee with the Distribution Management System Group Novi Sad, Republic of Serbia, from 2000 to 2005. Her interest is in planning and Ilić et al.: DECISION-MAKING FRAMEWORK AND SIMULATOR FOR SUSTAINABLE ELECTRIC ENERGY SYSTEMS 49

Niklas Rotering (S’09) was raised in Germany and went to ETH Zurich in Switzerland for university education. He received the B.Sc. degree in mechanical engineering with a focus on thermodynamics in 2007. Upon completion of the B.Sc., he chose to concentrate on electric power systems during his graduate education. He enrolled in the Master’s program in Energy Science and Technology at ETH and successfully graduated after writing his thesis at Carnegie Mellon University, Pittsburgh, PA, in 2009. He is currently working toward the Ph.D. degree at the Institute of Power Systems and Power Economics, RWTH Aachen, Germany, where he is studying under Prof. Albert Moser.

His research interests include electric vehicles, power system economics, and renewable grid integration.