Towards Next Generation Intelligent Energy Systems: Design and Simulations Engines

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Abstract— **The aim of this paper is to briefly present the overall objectives and the expected outcome of an on-going effort concerning the design the implementation and the analysis of next generation intelligent energy systems based on Anticipatory control and a set of ICT emerging technologies and innovations.**

Keywords— Smart Grid, Energy Markets, Power Flow, Price Elasticity

I. INTRODUCTION

Concerns about global climate change, resource limitations and economic stability drive a worldwide transition to smart energy. In advanced power systems, or smart grids, renewable generation, smart meters and novel storage technologies are modernizing the electricity infrastructure at an unprecedented rate. No one can really predict what the power infrastructure of the future would look like. It will likely be not a single network, but a network of networks, a network of smart grids (a system referred to as energy internet). The result will be a more difficult network to manage – in addition to stochasticity on the demand side; it will have stochasticity on the generation side. Yet, like existing power networks, the advanced power systems of the future would have to balance efficiency and reliability. And when this happens, reliability will always be given the priority. Even with this assumption, reliability is not guaranteed. It has been estimated that annual loss due to service interruption in the US is about $80 billion. A comparable quantity is estimated in Europe. The cause for each interruption might be different. But the principal reason is that generation and delivery capacity fails to provide sufficient safety margins, which may be further reduced due to poor management and bad regulation. Investing on more generators and better delivery systems (transmission and distribution) is an answer which suffers from some severe limitations.

It is expected that there will be an unavoidable and unprecedented increase on power demand (particularly due to electrification of transportation) and consumers will have higher expectations for the service, both on quality and quantity. On the other hand, resources are limited and the investment on exploiting them is a lengthy and expensive process. In this view of the future, it is very likely that safety margins may be reduced even further and more service interruptions will occur. A growing number of basic and applied research projects is underway to address this challenge. Most are focusing on responding to a plethora of emerging needs in smart grids components, sensors and devices. A significant number considers system-level management issues [1]. The proposed approach, however, is fundamentally different from past and ongoing ones. Inspired by the observation that a significant portion of the energy generated is lost due to inefficiency in operations, it considers energy efficiency as a new energy resource the development of which has dual storage and generation characteristics with significant benefits to both network reliability and efficiency.

The rest of this paper is organized as follows. In the next section we describe the problem we aim to solve and in section III we present our solution to this problem and the three specific assumptions that drive our efforts. In section IV we briefly overview the associated state of the art and in sections V and VI we state the long term benefits anticipated from the proposed study and the expected concrete outcomes. Section VII contains our overall methodology and section VIII our implementation plan.

II. DECRIPTION OF THE PROBLEM

The power grid is in a healthy and stable state only when all its components (conventional power plants, renewable generators, millions of customer-loads, thousands of kilometers of transmission and distribution lines etc.) are appropriately configured. This is an extremely difficult optimization problem without an analytical solution. One of the best tools for addressing such problems is ADP, or approximate dynamic programming [2] also known as neuro-dynamic programming or reinforcement learning [3]. Another tool available is the multi-agent (or intelligent agents) approach, where the search for solutions, rather than the solutions themselves, is explicitly formulated. A framework (agent environment) is developed for components to interact with each other and some protocols are imposed on their interactions. With an effective agent environment and the right set of protocols, components can reconfigure themselves adaptively in order to survive in the system. The system then acquires a very desirable characteristic; self-healing. Whenever the system deviates from its optimal operating point, its components automatically reconfigure themselves to correct the problem.

The Internet is one example where all these things take place. In this sense, an Internet-type network is a favorable option for next generation advanced power systems. The new system can provide an unprecedented degree of flexibility to users, services providers, marketers, and regulators. Customers will be able to choose the service package that fits their budget and preferences, thanks to competition. Service providers will see more profits through organized production, a result of real-time interactions with customers. Marketers or brokers will have more information to plan more user-oriented marketing strategies. The regulation agency can operate to its maximal capacity by focusing effectively on mostly regulatory issues. Best of all, it will be a more reliable and more efficient energy infrastructure.

Unfortunately, the existing energy infrastructure is not immediately ready for upgrading to an energy internet. For example, most components, including millions of electricity meters, in the current electric power grid are passive with very limited communication and reconfiguration capability. Furthermore, necessary regulations are not in place for opening up the whole infrastructure.

Researchers and policy makers have recognized the gap and tremendous progress has been made on smart grids. “Smart grids” is an advanced concept with a number of unique features compared to their predecessors, including:

- Detecting and correcting incipient problems at their very early stage;
- Receiving and responding broader range of information;
- Possessing rapid recovery capability;
- Adapting to changes and reconfiguring accordingly;
- Building in reliability and security from design, and,
- Providing advanced visualization aids to operators.

Progress made on smart grids has enabled new and meaningful discussions on a full scale energy internet. Building such a network requires substantial amount of effort from diverse sectors such as technology, social science, and legislation. Even though the Internet is a full-fledged technology, some key differences between energy (especially electricity) and electric data, which is transmitted on the Internet, prevent a direct copy. They are as follows:

1. Compared to electric data, electricity is mainly generated centrally and consumed locally. Long distance transmission is critical and traffic control becomes important since routing options are usually limited. Bottlenecks are more likely to be inadvertedly created.
2. Electricity cannot be stored at a large scale, which is different from the Internet where data are stored and retransmitted. Storage, served as buffers, is an important stabilizing factor in a complex system. The lack of storage in the electric power grid makes it vulnerable to all kinds of instabilities.
3. The Internet uses a “Best-Effort” service model and the quality of service (QoS) is a secondary consideration. The energy network, however, assumes the opposite. The top priority for the service network is to satisfy customers’ demand anytime.

For the Internet, the problem is how to allocate the bandwidth so that data packets can be delivered efficiently. On the other hand, in energy networks, customers’ peak demand, which can occur at any time, will be closely monitored and forecasted so that generation/transmission/distribution and demand-side management options can be scheduled to meet this demand.

III. BASIC ASSUMPTIONS AND PROPOSED SOLUTION

The recognition of the above differences is a necessary step towards feasible smart energy systems. Of many possible solutions to address these differences, the anticipatory control methodology appears very promising. Anticipatory control is a set of tools that enables successful control actions based on a system’s projected states. The power of this paradigm comes from its future vision as compared to conventional approaches which use only current-state information to affect change. Anticipatory control consists of two parts, anticipation of future states and intelligent decision-making based on the anticipation. These two components, as discussed later, are the key to fill the gap. Our proposed solution is founded on the following the three assumptions A, B and C described below:

A. Intelligent management and sharing of information achieves virtual energy storage

As discussed above, the biggest obstacle for the advanced energy systems presented is the lack of significant energy storage capacity inside the network. Without any feasible solution in the horizon, we have argued that it can be achieved virtually via intelligent information management and sharing [4], [5]. The idea is to create a virtual energy buffer between customers and suppliers. Virtual storage can enhance whatever physical storage may be found at the level of the grid (such as pump-hydro); at the level of residences or business (such as appliances with batteries); and, at the level of other infrastructures (such as battery vehicles, in transportation).

A virtual energy buffer is implemented through a demand side management strategy which is built upon the practice of dynamic data driven paradigms. With the emergence of intelligent meters, it is possible to dynamically schedule the use of electricity of every customer. This dynamic scheduling will create a sheet of virtual buffer between generation and consumption as we argue here, as shown in Figure 1. Under the new paradigm, the consumption of electricity of every customer is intelligently managed. Customers don’t power up their electricity-hungry machines at will. Rather, the machines themselves make smart decisions after balancing costs and benefits. For example, some non-urgent activities, such as laundry, can be scheduled for sometime during the day or night when electricity is abundant and cheap. The costs of the electricity are determined by the supply-to-demand ratio and the capacity of the network to transfer the resources. This managed use of resources is analogous to the access control widely used in the Internet. A buffer between generation and consumption is therefore created, virtually. No physic laws are broken. The electricity is still actually consumed when generated and all circuit laws are obeyed including regulatory frequency and voltage criteria [6]. However, from the customer point of view, with dynamic consumption scheduling the resources (electricity) are created and then stored somewhere in the power grid before they are used [7]. The analogy is shown in Figure 1. The virtual buffer may greatly increase the stability of the power grid.

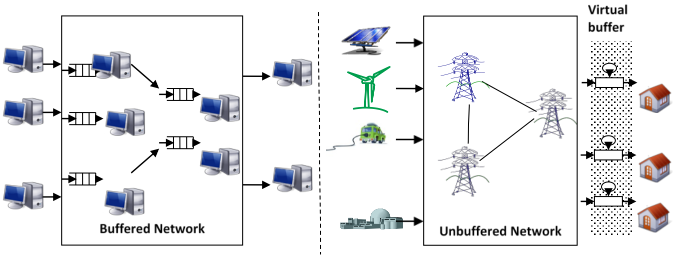

Figure 1: Internet (left) and intelligent power grid with virtual buffers (right).

Dynamic scheduling has to be carried out by software (intelligent agents). The intelligent agents will act on behalf of their clients; making reasonable decisions based on an analysis of the situation. One of the most important capabilities an agent has to possess is anticipation. The intelligent agent needs to predict its client's future consumption pattern to make scheduling possible. In other words, nodal load forecasting capability is an essential element of such a system.

Intermittent supplies, especially from wind, generate power that varies over time. Different types of storage function differently because of this and create different quantities of available storage as well as different patterns of storage the history of which is also a factor in how energy is stored and released. Developing optimal control policy for the storage and withdrawal of energy is a non-trivial problem.

B. Price Elasticity can effectively manage the uncertainty

As presented earlier, prediction is the cornerstone of the energy internet. However, accuracy is one of the major concerns for using prediction data as the basis for generation. Uncertainty is always associated with predictions and uncertainty may grow to an unacceptable level when millions of predictions are summed up. To circumvent this problem, a second assumption is presented, which is that: *price elasticity can be used to effectively manage uncertainty.*

This assumption is analogous to the one used in feedback control systems. Measurements are fed back as references, with which the controller can use to adjust its outputs adaptively. As a result, the controller itself need not be very accurate. Similar conclusions can be drawn here. Provided there exists a feedback loop between customers and suppliers, prediction errors will be corrected adaptively. The best feedback mechanism is provided by price elasticity, particularly *short-term elasticity*. A good short-term price elasticity model provides an estimate on the customer's purchasing willingness with respect to the change of price. Through this tool, customers and suppliers can perform dynamical negotiations to achieve a delicate balance between generation and consumption, even with less accurate load forecasting.

C. Integration of Physical Storage (Battery Vehicle BV) stabilizes Smart Energy Systems

The battery capacity of each BV is small in terms of kWh storage (typically 1-30 kWh range). This capacity limitation restricts consequently the "supply-side resource" capability of each BV. Thus, for effective integration into intelligent energy systems we need to have aggregation of BV into a collection with capability to impact the grid as shown in Figure 2. We take into account various sources of uncertainty, including, but not limited to, time of arrival, parking time, state of charge, storage of the vehicle, and, demand. We will show that BV storage is a convex function. For the aggregated BVs, the Central Limit Theorem (N>30) may justify the representation of the various random variables by normal distributions (George Gross, personal communication, 2009).

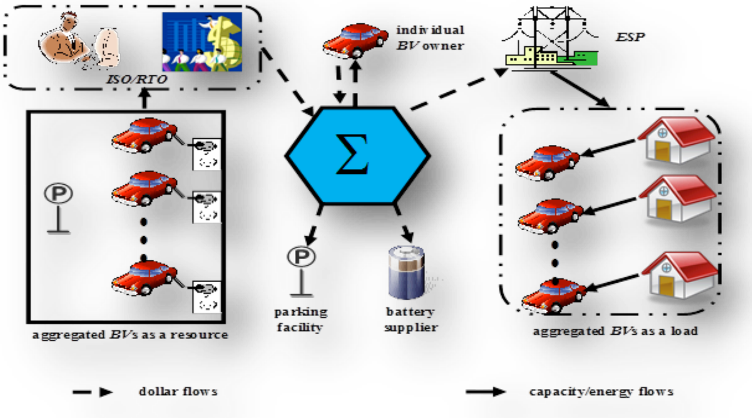

Figure 2: Aggregated BVs as storage and release of power in a price-incentivized architecture

IV. THE STATE OF THE ART

There are many possible architectural candidates for intelligent power systems as long as they satisfy the abovementioned assumptions. In this section, an example architecture will be delineated and discussed. The example was developed by the *Consortium for Intelligent Management of Electric-power Grid* *(CIMEG)*. CIMEG advanced an anticipatory control paradigm with which power systems can act proactively based on early perceptions of potential threats. It uses a bottom-up approach to circumvent the technical difficulty of defining the global health of a power system at the top level [4].

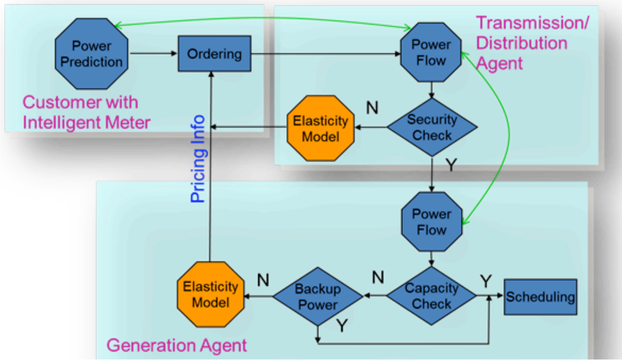

Figure 3. Interactions among agents

In intelligent power systems, customers play a more active role than in the existing power systems. Lots of solicitation and negotiations are involved, as shown in Figure 3. Here the customer, who is represented by an intelligent meter, predicts a future need for electricity and places an order in the market. The amount of the order is influenced by the market price of the electricity, which is further determined by the difference of the demand and supply and also the capacity of the network. Economic models with price elasticity are used in the process. The active interaction between customers and suppliers create a virtual buffer between consumption and generation as discussed earlier.

To conquer the computation and communication bottlenecks, we partition the environment an agent sees into *local* and *global* components. The two environments call for different agent tools. The local environment of an individual agent includes its immediate neighbors with which the agent can exchange information in a direct manner. The global environment consists of the rest of the system and often contains too much information for an agent to handle effectively. To overcome this limitation we propose a specialized "news agent" that collects and digests information in a system-wide manner. Our goal is to show that once every agent in a power system has both local and global visions, an unexpected disturbance in the system could be isolated and diminished before progressing disastrously. And eventually, the system's integrity is assured by the collective actions of all agents.

The novel concepts proposed are realizable with the aid of advanced simulation engines which will be capable to handle a plethora of dynamic interactions among thousands even millions of agents or devices. GridLAB-D has been developed by the US Department of Energy and Pacific Northwest National Laboratory in collaboration with industry and academy partners. This is an open source open architecture simulation environment that can serve as the main implementation toolbox for our purposes. With a number of tools for smart grids and proven power flow software undergirding it, GridLAB-D can accommodate agent architectures and provide simulation and analysis tools for power distribution systems that may include millions of devices. It provides more accurate results in unusual situations and is capable of multiple time scales processing ranging from sub-seconds to several years.

V. THE LONG TERM BENEFITS

The challenge of double stochasticity and its corollary implications on network reliability drives a worldwide research agenda on advanced power systems of the future. Many European research and development projects address the novel technological needs in components, sensors, devices and management algorithms for smart grids [1].

The proposed approach is fundamentally different in that it addresses the relation between energy efficiency and reliability in a novel, potentially game-changing way. Managing nodal demand in an anticipatory manner (through predictions of future states and intelligent management of uncertainty) is equivalent to making available new generation and storage resources that increase both energy efficiency and reliability.

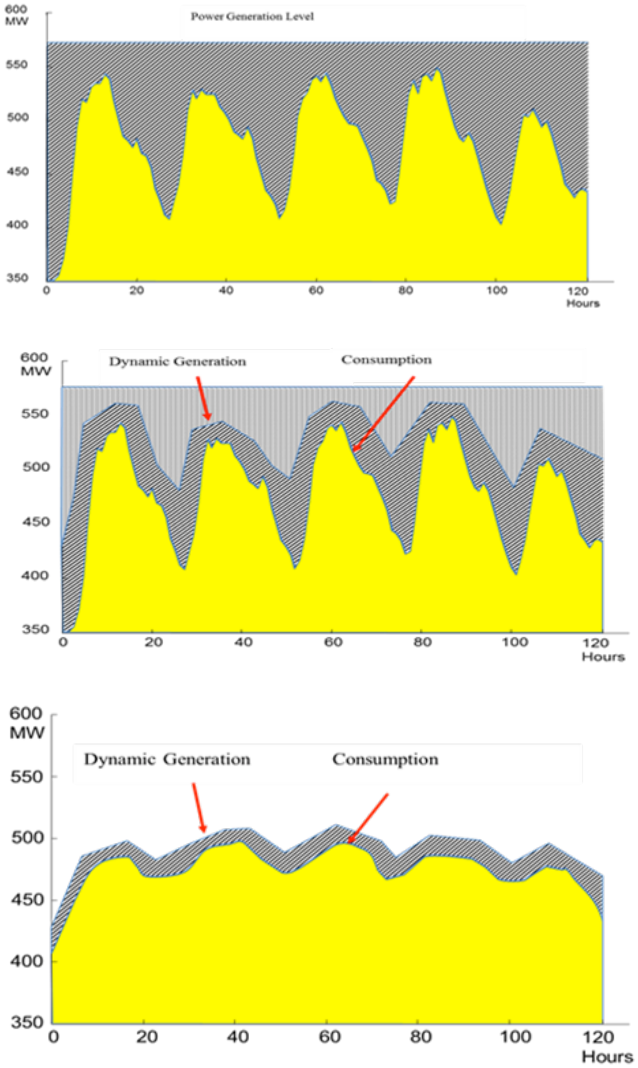

Figure 4: Energy savings through anticipatory management and virtual storage. Energy demand (yellow) and energy waste (grey).

In a sense, the proposed approach solves the **storage** problem more through **computing** and less through **electrochemistry**. Since our technological capacity to compute (and hence anticipate) far exceeds out physical capacity to store energy, the proposed approach has the potential to revolutionize the entire energy infrastructure with profound impact on many aspects of modern society including lasting and long-term environmental and economic implications. The approach facilitates the integration of three major modern infrastructures: the **power grid**, the **Internet**, and the **transportation**. Success in this project can be game-changing bringing enormous economic benefits including benefits through quality, reliability, as well as generation and emissions reductions the economics of the last being difficult to accurately estimate at present but the future cost of which should not be underestimated at all.

Figure 4 shows the benefits of anticipation and price-directed demand on a mid-size smart grid of max power in the range of 600 MW. The power pattern for an entire working week (five peaks = five business days) is shown where it can be seen clearly that there are significant differences in night and daily type of demand. Ideally, power generation must be always in a position to meet and exceed by a safety margin of approximately 10% the peak demand (demand is shown by yellow). As a result a significant amount of energy (represented by the shaded area) it is actually wasted. In the graph the wasted energy is approximately 40% of the energy actually used.

VI. THE CONCRETE OUTCOMES

The main outcome of our efforts will be the scientific results which elucidate several important concepts and enable equally important technological solutions. Another important outcome will be an innovative, web based, open source and open architecture advanced simulation platform capable of numerous needed studies including, but not limited to, network quality, efficiency and reliability, connectivity and complexity, and management of desirable effects and undesirable consequences (e.g., the curse of dimensionality and the double stochasticity of future power networks). Our platform will be founded on the solid grounds provided by standards, best practices and software systems as these are depicted in Figure 5. All the above and beyond will be available at http://hephaestus.ireteth.certh.gr/.

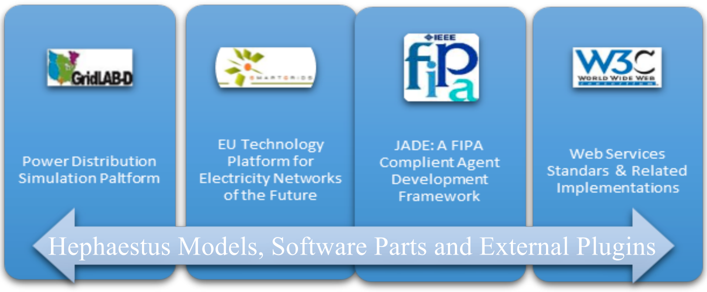

Figure 5. The components of the proposed simulation platform.

VII. HEPHAESTUS METHODOLOGY

Smart grids require significant efforts beyond the scope of a single project. We intend to construct a complete simulation environment, called **Hephaestus,** as outlined below**.**

Smart meter with unique address and communication capability: This is probably the most fundamental requirement on the side of hardware. Everything will start from a meter installed on the customer side. The interactions between customers and suppliers (including any middlemen, such as retailers) occur in such a high rate that manual operation is impossible. Basic hardware support is needed for automatic and real-time communication between customers and suppliers. This necessitates a smart meter with a unique and addressable identifier and two-way communication capability. In our implementations smart meters will be realized through software agents and web services.

Forecasting capability: Prediction and anticipation are the essential stabilizing forces in a complex system. The more information about the future is known, the better planning can be made. For an energy internet, it is crucial that customers' energy usage patterns can be predicted with a degree of certainty. In this project, two forecasting models will be investigated, one for load forecasting and the other one for disturbance forecasting. The load forecasting model will be used to ensure that the power flows under the thermal limit of the grid. The disturbance forecasting model provides information that is useful to prevent the disruption of the service due to factors such as voltage and frequency. There are plenty of tools available for this purpose thanks to extensive research efforts in the past. Using parametric (statistical) or non-parametric (neural networks) or hybrid (fuzzy logic) methods, these tool can accurately predict a customer's short-term demand.

Multi-resolution agents: The real time operation in an energy internet requires the application of intelligent agents. Intelligent agents act on behalf of their clients, who can be actual customers, power grid operators, electricity brokers, or non-human entities such as transformers, generators, transmission lines. Intelligent agents are equipped with sufficient knowledge so that they can act rationally. Conventional wisdom suggests that each intelligent agent should take actions to pursue maximal benefit for itself. This assumption is made in order to simplify the operation of intelligent agents. However, it may result in some unwanted side effects that have been identified by many researchers especially in game theory. These side effects are harmful to the health of the whole system and appropriate actions should be taken to avoid that.

In classical game theory, an agent is given access to all information if available, such as the possible actions and outcomes of other agents. We argue that this is an unrealistic condition. In classic game theory, an agent is able to choose the best strategy (i.e., act rationally) if it can examine all possible scenarios. Experimental data contradicts such conclusions (see Prisoner's Dilemma). Human beings sometimes act irrationally according to game theory. A human being does anticipatory reasoning, which means that when making a decision the consequence has been taken into consideration. The major difference with classic theory is that human being does not have an accurate prediction for things in very far future, which in part explains why a human being sometimes acts irrationally according to classic theory [8]. A human being sees the future in two different time scales, short term and long term. In the short term scope, we can make very accurate estimations. In long term scope, we have to make estimations with increasing degree of uncertainty. Therefore, a more realistic agent must possess a multi-resolution vision. We propose it as a second principle (assumption) for agents. We shall show that this is not only a reality but also a stabling factor for complex systems.

Agents compete for their maximal benefits (payoffs). This assumption excludes them from collaboration in many situations (such as Prisoner's Dilemma). For agents with multi-resolution vision, collaborations are possible because the future is not clearly mathematically defined. For example, in the Centipede game, if both players know exactly what the other player's move (future), the first player is likely to choose to defect on the first play because this is Nash equilibrium and he has no incentive to choose the other option (cooperation). However, in reality, the future that players can see is not a clear picture. But the most important information a player can read from this fuzzy picture is that the payoffs would be much better in the *future*. A player is likely to choose to cooperate if he knows he can gain more by passing the piles. Then he would be very likely to choose cooperate in order to maximize the personal gain.

Short-term price elasticity model: Price elasticity is used to characterize the sensitivity of customers to the change of the price. In the case of electricity, the price elasticity measures how the price change impacts the customers' willingness to consume power. A good short-term price elasticity model provides the basis for interactions between customers and suppliers.

Web service architecture: According to W3C "*Web service is a software system designed to support interoperable machine-to-machine interaction over a network. It has an interface described in a machine-processable format. Other systems interact with the Web service in a manner prescribed by its description using SOAP messages, typically conveyed using HTTP with an XML serialization in conjunction with other Web-related standards*". In **Hephaestus** we consider Web services an abstract notion that must be implemented by a concrete agent. The agent is the concrete piece of software or hardware that sends and receives messages, while the service is the resource characterized by the abstract set of functionality that is provided. To illustrate this distinction, you might implement a particular Web service using one agent one day (perhaps written in one programming language), and a different agent the next day (perhaps written in a different programming language) with the same functionality. Although the agent may have changed, the Web service remains the same [9].

VIII. IMPLEMENTATION PLAN

Hephaestus implementation is organized in the following 5 workpackages.

1. **Forecasting Models:** Anticipatory controls are possible only when future states of the system can be accurately estimated. Forecasting models are developed for this purpose. In this project, the following two models will be investigated: **(1)** *A load forecasting model* that provides user electricity consumption information in both short and mid-term. The forecasting information will be used for scheduling generation, distribution, and consumption. **(2)** *A disturbance forecasting model* takes into considerations a variety of information and predicts any possible degradation on the quality of the service. The prediction is used in conjunction with the load forecasting to regulate the generation, distribution and consumption of the electricity.
2. **Agent Platforms:** The intelligent agent platform is the running environment for our simulation. The goal of this Workpackage is to design an environment to efficiently support all agent functionality. This work will be based on the existing tools already available from GridLAB-D and expand and incorporate the following items: **(1)** Three types of *intelligent agents* generation agents: distribution agents and customer agents. **(2)** An *intelligent agent platform* to support agents and their functionality, especially their communication capability.
3. **Intelligent Information Management:** Acquiring, processing, and managing information intelligently are the key to define a smart energy system. Through **Hephaestus**, we intend to demonstrate and prove that prediction/anticipation and dynamic response via pricing signals are two critical elements for a smart energy system. Specifically we will develop: **(1)** A *mathematical foundation* that provides theoretical foundation for **Hephaestus**. Factors to be considered include stability, efficiency and convergence. **(2)** *Short term price elasticity models* to provide the response of consumption according to the change of price. The response is the basis for the negotiation process that involves generation/distribution/customer agents. **(3)** *Multi-resolution* vision is an important capability for intelligent *agents*. Two kinds of vision will be implemented in this project, short-term vision and long-term vision. Short-term contains most accurate information while long-term vision consists of approximated information.
4. **Integration and Testing:** Integration and testing will involve significant effort to ensure that **Hephaestus** is a user-friendly, reliable tool that can be used with high confidence on the part of the user and high fidelity and

reliability regarding output. The following tasks are foreseen **(1)** *Data collection: Data* utility and power grid data available to us under agreements made in previous CIMEG research as well as data from local sources will be utilized. The data will be suitably processed to protect privacy. **(2)** *Web services architecture:* We integrate our system components in a loosely coupled manner that allow for a more natural, effective and accurate deployment of our simulation system. **(3)** *Study case implementation:* A moderate size study case will be constructed. The test case will consist of a mixture of generator, distributions, and customers. The study case should be typical and manageable. **(4)** *Testing and verification:* A metric will be first developed for evaluating the performance of complex system. Test cases then will be constructed for verification.

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