

Energy Ecologies—Models and Applications

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Abstract

We define a new approach to and view of energy management. Energy Ecologies bridge the gap between electrical generation, storage, and use, and the interchange and fungibility of all types of energy resources and energy consumption.

Within a facility or microgrid, definition and design has typically concentrated on electrical energy, with some work considering thermal mass for buildings. [1] We apply net energy flow modeling [2] [3] considering microgrids as the fundamental architectural unit. [4]. We also exploit the smoothing of energy flows that is a key value for the smart power grid, and we anticipate, for the smart energy ecologies. [5]

We gain a great deal by applying a consistent framework for all of the energy suppliers and consumers within a microgrid. For example, a thermal industrial process, given appropriate equipment, may be carried out with energy from electricity resistance, natural gas burners, adjustable Combined Heating and Power (CHP) units, hot water, steam, and more.

For energy surety, under internal or external loss and damage, the model can be used to determine energy economics and guide selection of sources and paths.

We define the Energy Ecology Conversion Matrix for a particular node at a particular time by dynamically tracking the costs and economics of potential use. We then describe algorithms for specialization of a broad area Energy Ecology Conversion Matrix by restriction to the particular facility and consumption/supply capabilities, greatly simplifying information and decisions made in carrying out the business purpose(s) of that facility. Constraints may include regulatory, physical, and supply.

The Energy Ecology framework approach integrates disparate techniques for choice and timing of consumption and supply, yielding a simplified and systematic way to characterize the benefits and costs of energy in a localized sense, and considering all useful sources of energy. This allows the application of standards and technology already developed and being deployed for the smart grid.

By extending these interoperation and market interaction approaches for the Smart (Electrical) Grid to the Collaborative and Smart Energy world we facilitate creation of smarter and energy-efficient microgrids, facilities, and enterprises scalable and replicable across all forms of energy, addressing key facility automation and business requirements.

Topics: Transactive Operation, Economic/Regulatory Policy, Business Models, Renewables/DER, Policy-Based Operation

1. INTRODUCTION

We know from introductory physics that energy is conserved, and may be transformed from one kind to another, albeit with losses.

Another way of saying this is that energy is fungible—it is changeable in kind under some assumptions. We can store energy for later use—through batteries, thermal storage, or the creation of manufactured goods that embody the energy used in their production.

Without loss of generality, and abstracting details of implementation, we address the fundamental architectural unit, the microgrid. We could as well say facility, device, or actor.

But we go beyond electrical energy microgrids [6] and extend the perspective to all kinds of energy, and to both the ecology and economy of energy.

In this paper we define a way to quantify those conversion costs (operational and capital both), and make it easier to select energy sources and conversions. We define and model the energy ecology of a microgrid.

The root for the words ecology and economy is the Greek οικος. It is fitting to tie both together to deepen our understanding of how energy is exchanged, transformed, and used within a microgrid.

Our deepened understanding supports improved management of energy, addressing costs, availability, and selection.

2. BACKGROUND

Within a facility or microgrid, definition and design has typically concentrated on electrical energy, with some work considering thermal mass for buildings. [1]

We apply net energy flow modeling [2] [3] considering microgrids as the fundamental architectural unit. [4].

We also exploit the smoothing of energy flows that is a key value for the smart power grid, and we anticipate, for the smart energy ecologies. [5] Smoother, more valuable consumption and production of energy is a key value from microgrids, micromarkets, and structured energy.

3. EXAMPLES

We start with several examples of current practice. A *microgrid* can be analyzed by looking at its energy in- and out-flows. We further refine the model of [3] and [2] by considering the *kind* of energy¹ not just the quantity.

¹ (Cox & Considine, Structured Energy & Autonomous Transactive Operation, 2013) addresses energy in general,

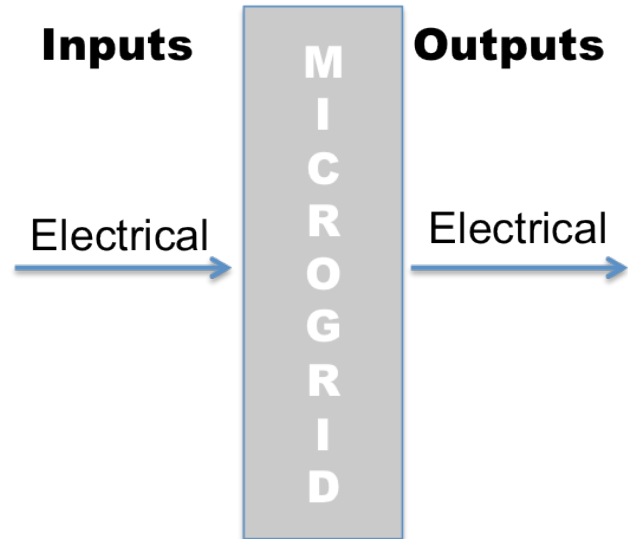


FIGURE 1 ELECTRICAL STORAGE SCHEMATIC

3.1. Electrical Storage

See Figure 1. The storage unit (which we model as a microgrid) takes electrical energy as input and provides a time delayed electrical energy output.

3.2. Ice Storage

See Figure 2. An ice storage unit, such as an Ice Bear [7] consumes electrical energy and produces thermal energy (cooling) over time. This differs from a standard air conditioning unit in that it shifts energy use by consuming it before it is needed, and storing the product for later use.

not only electrical energy, but addresses energy flows as a unitary concept.

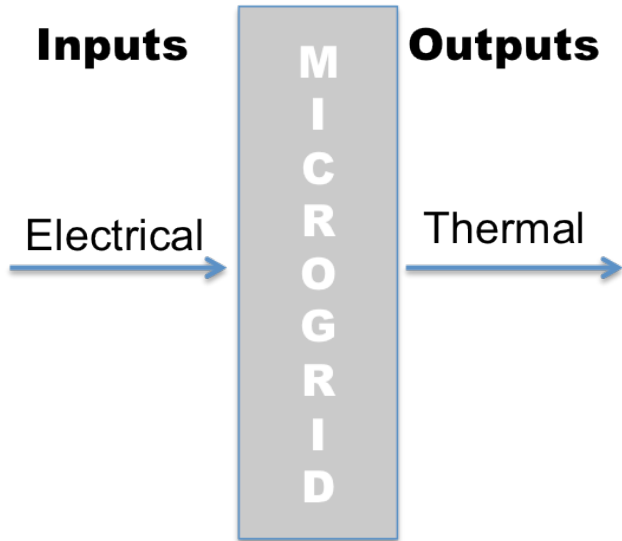


FIGURE 2 ICE STORAGE SCHEMATIC

We could separately model storage as in Figure 3, suggesting that the purpose of the node involves storage, or delayed output. We simplify the exposition by not including such implied storage and/or delays.

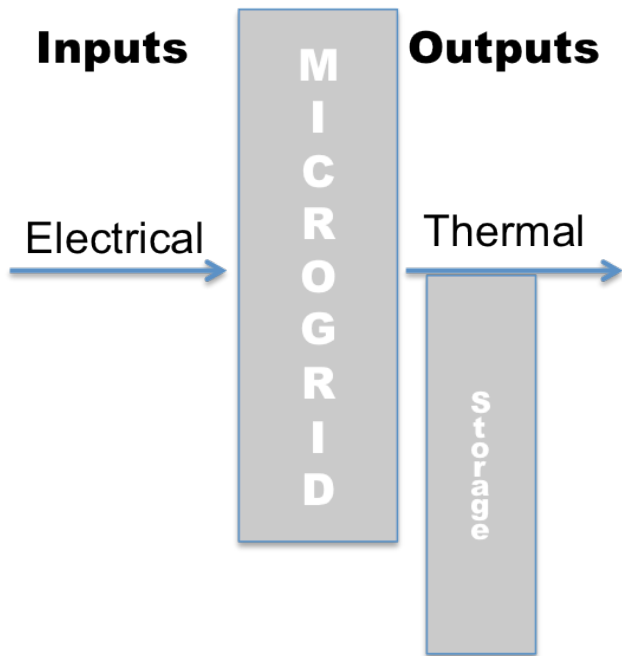


FIGURE 3 ICE STORAGE SCHEMATIC ILLUSTRATING EXPLICIT STORAGE

3.3. Multi-Fuel Units

Many systems are designed to use more than one energy source. These are often called *dual fuel* (if two energy kinds are accepted).

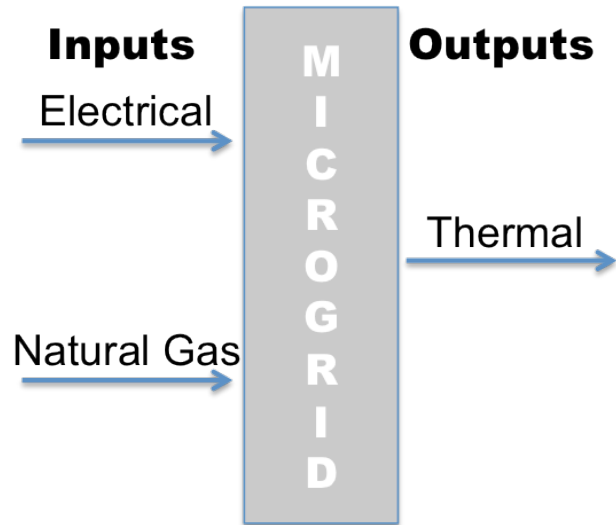


FIGURE 4 MULTI-FUEL SCHEMATIC (TWO ENERGY SOURCES SHOWN)

Examples include dual-fuel boilers (gas and electric), and process equipment that might use electrical resistance heat or hot water/steam.

3.4. Missing Waste Heat

These examples are at a high level of abstraction. Devices, and microgrids, that are not perfectly efficient also produce heat. That waste heat may be reused (e.g. for pre-heating water before a boiler), or not (waste heat from electronic components enter into what we might call the *thermal ecology* of a facility).

We will not generally show such waste heat unless it is also input to another microgrid at the level of abstraction we're using.

4. GENERAL MODEL

4.1. Abstract Model

We consider a microgrid with n inputs and m outputs; see Figure 5.

Each input and output has the following attributes.

- Kind—Kind of energy, e.g. Electrical, Thermal
- Quantity—Quantity of energy, measured e.g. in Watt-hours or Joules

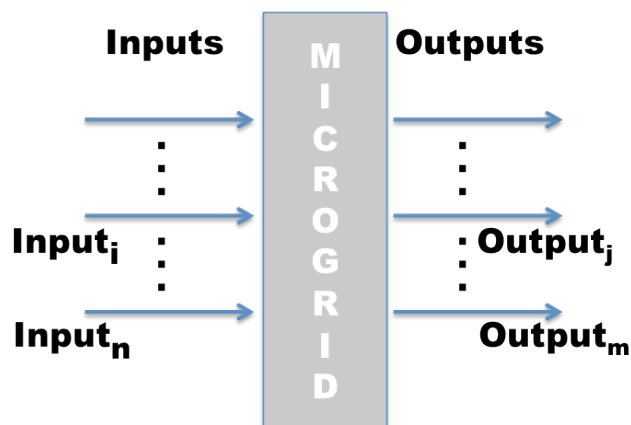


FIGURE 5 ABSTRACT MODEL WITH INPUTS 1..i..n AND OUTPUTS 1..j..m

For example, Kind ($Input_i$) could be electrical, and Quantity ($Input_i$) might be 1 kWh.

We simplify our notation by labeling the Inputs and Outputs with the respective Kinds of energy.

In the following subsections we describe a detailed example using three kinds of energy and all reasonable conversions.

4.2. A Matrix Approach

For simplicity we will assume in this section that

$$Kind(Input_i) = Kind(Output_i)$$

And that $m = n$.

We define the *Energy Ecology Conversion Matrix*, or simply *Conversion Matrix* as an $N \times N$ matrix where the rows are input energy kinds, and the columns are output energy kinds. See Figure 6, where we show only the capability of conversion.

Input				
Natural Gas				
Electrical				
Thermal				
	Natural Gas	Electrical	Thermal	Output

FIGURE 6 ENERGY ECOLOGY CONVERSION MATRIX—SHOWING CAPABILITIES ONLY (RED SQUARES)

While it might be useful to have a *no change of kind* conversion, we do not mark the diagonal, so our example matrix does not anticipate e.g. natural gas-to-natural gas conversion.²

With the proper equipment, natural gas can be transformed to electrical energy (a natural gas-fired generator) or to thermal (a natural gas-fired boiler).

However, there are no commercial technologies today that directly convert electrical energy to natural gas; likewise for thermal to natural gas.³

Finally, thermal energy can be transformed to electrical energy by use of (say) a boiler to spin a turbine.

The actual equipment available determines the highlighted squares; the abstract conversion is reflected in Figure 6 and should be read “there is some way with the equipment available to transform $Input_i$ to $Output_j$.”

4.3. Efficiency

The fact that we *can* convert energy from one form to another does not imply that there are no losses, per the laws of thermodynamics.

² Some sorts of loop systems, e.g. circulating chilled or heated liquids, would be on the diagonal: the kind is the same, but the energy content may be higher, lower, or the same.

³ But see [15] Note that the likely production rates are slow, and probably not sufficient for every day use. For the 10 minute commuter, it *might* be enough to keep the tank full. It is interesting to speculate about an imagined package unit coupling solar PV with the home generator in order to keep the generator tank full. See also <http://www.airfuelsynthesis.com/index.php>.

So we must consider the efficiency of the specific equipment available for each conversion pair.

Ignoring details of the inputs and outputs, we insert some typical efficiency numbers drawn from the literature; we express efficiency as the proportion of a unit of input energy that is delivered to the output.

Input	Output	Efficiency
Natural Gas	Electrical	.65
Natural Gas	Thermal	.99
Electrical	Thermal	.99
Thermal	Electrical	.50

TABLE 1 CONVERSION EFFICIENCY (EXAMPLE)

The efficiencies are shown in our Conversion Matrix in Error! Reference source not found. Figure 7.

Input	Natural Gas	Electrical	Thermal	Output
Natural Gas		0.65	0.99	
Electrical			0.99	
Thermal		0.50		

FIGURE 7 CONVERSION MATRIX SHOWING EFFICIENCY OF CONVERSION

4.4. Input Costs

In parallel with the start of Section 4.3, the fact that we can convert energy from one form to another does not imply that all conversions are economically efficient and effective. In this section we look at the input costs and computing the output costs.

We now have enough information in the Conversion Matrix to determine the cost of an output, given additional information on the cost of the input (actually or potentially) used. These costs, of course, must be normalized to a single unit of measure for energy. We will use cost in cents per

kilojoule, and actual prices for Natural Gas and Electrical Energy⁴

This information will be in the Input Cost Vector. For our example, the vector has three positions. See Figure 8.

Input Cost	
Natural Gas	8
Electrical	14
Thermal	11

FIGURE 8 INPUT COST VECTOR IN CENTS PER KJ

4.5. Output Costs

Applying the input costs, we get the resultant cost matrix. We call the result the Cost Conversion Matrix, which is an NxN matrix computed as above from the Efficiency Conversion Matrix and the Cost Matrix. See Figure 9.

Input	Natural Gas	Electrical	Thermal	Output
Natural Gas		12.3	8.1	
Electrical			14.1	
Thermal		22.0		

FIGURE 9 OUTPUT COSTS IN CENTS PER KJ (PENDING CORRECTION)

So if we need electrical energy, we can produce it from natural gas at roughly half the price of a direct thermal conversion; for thermal output natural gas as an energy source is roughly half the cost of electrical energy.

⁴ With a number of simplifying assumptions these are approximate costs for Northern New Jersey, 2012

4.6. Embodied Energy

A microgrid (or node) typically exists to perform some function, whether it is generation of net energy, or creating or adding value to a product.

For example, the production of aluminum involves large quantities of energy. The cost of finished aluminum from the smelter includes a substantial cost for energy consumed in the production. We may consider the finished aluminum as embodying energy.

In a similar way, the creation of finished products embodies the energy used in their creation. We may consider that energy as another output from a microgrid.⁵

Accordingly we add an additional output to Figure 5, redrawn as Figure 10.

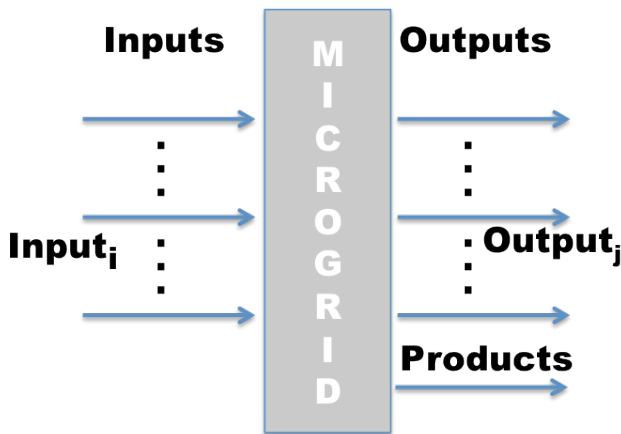


FIGURE 10 EMBODIED ENERGY SHOWING PRODUCTS AS AN ENERGY OUTPUT

This allows a closer balance between inputs and outputs in the network.

4.7. Putting It All Together

Even this general model is a simpler than current delivery contracts imply. For example, there are meter and supply charges, and the price may vary as consumption in a designated period implies.

We've addressed some of the complexities of describing ratchet prices and variable costs elsewhere. [8]

We have taken information from a number of places—device specifications, possibly dynamic prices, and capability of conversion—and shown how to combine them into actionable information for energy consumption decisions.

⁵ For simplicity we do not consider the efficiency of conversion of energy into product, but consider the embodied energy to be that put into the product's creation.

4.8. Analysis

We started with matrices showing efficiency and cost of energy inputs. These reflect a subset of $\mathbb{E} \times \mathbb{E}$, the set of possible energy inputs and outputs.

We apply three filters and sets of constraints to the full cross product:

- (1) Feasibility Filter: Can we transform the given input to the given output? (See discussion in Section 4.2)
- (2) Economic Filter: What is the cost for the resultant energy output? (See discussion in Sections 4.4 and 4.5)
- (3) Policy Filter: What can I afford to pay? What is the value of the result (e.g. in contribution to my mission)?

Finally, there are constraints including maximum and minimum supply, rate of delivery, time of delivery and more. These energy services, for Electrical Energy, are completely supported in OASIS Energy Market Information Exchange [9] and Energy Interoperation [10]. We will discuss extensions for full Energy Ecology implementation in Section 6 below.

5. OPTIMIZING THE ENERGY ECOLOGY

There are several optimizations we can apply to the general Energy Ecology model.

We already restrict the matrices to the kinds of energy available and consumed in the microgrid/premises.

We may make assumptions on uniformity of prices and costs across the microgrid. As far as prices, the scope of the relevant market is the microgrid; the balance of supply and demand and the corresponding clearing prices are determined within the microgrid, so this seems a safe assumption.

Efficiency of conversion is node-dependent, but might be presumed to be the same *a priori* value for all nodes and conversions, reducing the number of matrices from one per node to one per microgrid, with the concomitant inaccuracies.

6. TECHNOLOGIES AND TECHNIQUES

6.1. Standard Interconnection

The communication of required information on energy inputs and outputs is addressed in OASIS Energy Market Information Exchange and Energy Interoperation, created in response to a request by the NIST Smart Grid Project (See [11]) for cross-cutting price and product definition, and for communication of Demand Response and Distributed Energy Resource requests and responses; the latter was

extended in implementation to define a simple transactive energy approach (of which e.g. [12] is a simplified profile).

6.2. Not Just Electrical Energy

These standards and technologies were undertaken to address electrical energy, but the standards and technologies were designed from the beginning to address not only electrical energy, but all forms of energy for which markets, prices, and products can be defined.

In this section we detail the extensions to the EMIX resource model needed to implement Energy Ecologies.

There are no changes necessary for the Energy Interoperation model, as prices, product definitions, and interaction are based on the EMIX resources we describe here.

6.3. EMIX Resources and Extensions

EMIX Resources are part of the definition of Power Products, and are the objects that provide electrical energy. Attributes of energy provided include amount, product definition, ramps, maximum, minimum amounts, and voltage.

In this section we sketch an appropriate set of extensions to enable price and product definition for combustible gases (including Natural Gas, Propane, and Hydrogen) and for thermal energy. We express this sketch in tabular form, and deliberately leave out many details to clarify the exposition.

The characteristics and product definition for electrical energy is in the Power schemas for EMIX; a `PowerItem` includes units, a `Système International (SI, or Metric)` scale code, and in each subclass a set of `Power Attributes`. We focus only on energy in Table 2.

<i>Characteristic</i>	<i>Electrical</i>	<i>Combustible Gas</i>	<i>Thermal</i>
<i>How much?</i>	Quantity	Quantity	Quantity
<i>Units</i>	J, Watt-hour,...	J, BTU, Therms	J, BTU
<i>What pressure?</i>	Voltage	Pressure	Pressure
<i>Ramps, capability</i>	Array of Ramp Segments	Array of Ramp Segments	Array of Ramp Segments
<i>Other</i>		Chemical content description	Inlet, outlet temperature, differential ⁶

TABLE 2 SOME CHARACTERISTICS OF ENERGY RESOURCES AND PRODUCTS—POSSIBLE EXTENSIONS TO EMIX ELECTRICAL POWER AND ENERGY

We exploit the extensibility EMIX provides to other forms of energy.

In this sketch Hydrogen gas fits well as a combustible gas, but other uses include operating fuel cells to directly produce electricity.

7. DISCUSSION

As we move to leaner energy systems without waste or surplus, the problem of intermittency grows. We face intermittent use: building services are now scheduled across the day, where once they had invariant requirements. We face intermittent supply, as renewable sources are introduced to the ecosystem. Many of these variations cannot be scheduled centrally. The core problem of aligning supply and demand has an ever more pressing temporal component.

In natural ecologies, a biome attains resilience through diversity. Even slight variations can give an organism a competitive advantage within a particular niche. Some organisms that seem too slow, too ugly, too inept are perfectly adapted for niches that no other organism can thrive in. So, too, in energy ecologies.

⁶ The difference in inlet and outlet temperatures determines the energy delivered; a range of permissible outlet temperatures determines the range of energy that may be delivered. These correspond to minimum and maximum energy for electrical energy, and should be considered as an alternative standardization.

For example, an English start-up, Air Fuel Systems,⁷ has demonstrated generating automobile fuel using air, water, and electricity.

What follows is speculative, as the authors have no direct knowledge of their product. They may be able to create a facility producing industrial amounts using surplus power from evening wind. It may be that their real niche is occasional power with a long connection time. When paired with a sporadically used generator, it could eliminate the need for deliveries to fill the tank. At an isolated outpost, it might supply an emergency cache of aviation fuel.

Many types of organisms interacting characterize a natural ecology. Systems which seem complete impractical in today's regimented energy markets may find their niche in tomorrow's energy ecology.

Light, simple, and universal mechanisms for exchanging minimal information between systems enable inexpensive ad hoc integration. With integration costs minimized, there is reduced need for homogeneity and maximum opportunity for introducing novel systems. Unique collections of commodity and special capability systems are the essence of Energy Ecology.

8. SUMMARY AND CONCLUSIONS

Energy Ecologies provide a framework to think about, plan, design, and operate microgrids, facilities, and devices.

We have shown how to apply standard techniques in graph search, matrix algebra, and sparse matrix algorithms to simplify the management of diverse energy sources and consumers within and across microgrids.

We have defined Energy Ecologies, defined a model and several simplifications of the model. Our proposed extensions to the EMIX resources and product types allow description of market operations, delivery, leveraging the standards that are the basis for OpenADR 2 profiles⁸, and which we anticipate will be broadly used building on the OpenADR [1] [13] deployments.

9. FUTURE WORK

Several questions could be considered in future work.

First, the standardization of extensions for EMIX resources and the use in the standard Energy Interoperation services needs to take place.

Second, the assumptions about uniformity of price, and the effects of assuming average efficiencies may guide operation approaches with limited complexity. The tradeoffs

and effect of miscalculations compared to the full model should be determined.

Third, other applications of our proposed extensions to EMIX product definitions and products present, including reports on estimated use (to compute pressure drops and DR-like events) for Natural Gas and thermal energy. These reports are already part of Energy Interoperation and proposed OpenADR2 profiles. This permits cleanly projecting usage and demand, as well as a simple information model and a clean service interface for communicating historical usage of energy.

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⁷ <http://www.airfuelsynthesis.com/index.php>

⁸ OpenADR Alliance, <http://www.OpenADR.org/>

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BIOGRAPHY

William Cox

William Cox is a leader in commercial and open source software definition, specification, design, and development.

He is active in the NIST Smart Grid Interoperability Panel and related activities. He contributed to the NIST conceptual model, architectural guidelines, and the NIST Framework 1.0.

Bill is co-chair of the OASIS Energy Interoperation and Energy Market Information Exchange Technical Committees, past Chair of the OASIS Technical Advisory Board, a member of the Smart Grid Architecture Committee, and of the WS-Calendar Technical Committee.

Bill has developed enterprise product architectures for Bell Labs, Unix System Labs, Novell, and BEA, and has done related standards work in OASIS, ebXML, the Java Community Process, Object Management Group, and the IEEE, typically working the boundaries between technology and business requirements.

He earned a Ph.D. and M.S. in Computer Sciences from the University of Wisconsin-Madison.

Toby Considine

Toby Considine is a recognized thought leader in applying IT to energy, physical security, and emergency response. He is a frequent conference speaker and provides advice to companies and consortia on new business models and integration strategies.

Toby has been integrating building systems and business processes for longer than he cares to confess. He has

supported and managed interfaces to and between buildings, cogeneration plants, substations, chilled water plants, and steam and electrical distribution. This work led to Toby's focus on standards-based enterprise interaction with the engineered systems in buildings, and to his work in the Organization for the Advancement of Structured Information Standards (OASIS).

Toby is chair of the OASIS oBIX Technical Committee, a web services standard for interface between building systems and e-business, and of the OASIS WS-Calendar Technical Committee. He is editor of the OASIS Energy Interoperation and Energy Market Information Exchange (EMIX) Technical Committees and a former co-Chair of the OASIS Technical Advisory Board.

Toby has been leading national smart grid activities since delivering the plenary report on business and policy at the DOE GridWise Constitutional Convention in 2005. He is a member of the SGIP Smart Grid Architecture Committee, and is active in several of the NIST Smart Grid Domain Expert Workgroups.

Before coming to UNC, Mr. Considine developed enterprise systems for technology companies, apparel companies, manufacturing plants, architectural firms, and media companies old and new. Before that, Toby worked in pharmaceutical research following undergraduate work in developmental neuropharmacology at UNC.

David Holmberg

David Holmberg is a researcher in the Engineering Lab at NIST. His work focuses on building integration into the Smart Grid and, more generally, communication of building-system data to outside partners. David serves as part of the NIST Smart Grid team, leading the Building-to-Grid domain expert working group and serving as NIST lead for a number of customer-interface related priority action plans within the Smart Grid standards effort.

He is convener of the BACnet Smart Grid Working Group (SG-WG) of the ASHRAE BACnet committee focused on commercial building automation system interactions with the smart grid. He also co-chairs the OASIS Energy Interoperation technical committee focused on developing a standard for demand response signaling, energy market transactions, energy usage and load communications and other cross-domain energy interactions. Research interests include information modeling to support standards development in addition to novel smart grid aware building control strategies.

David received his PhD from Virginia Tech, and joined NIST in 1997. Since joining the Mechanical Systems and Controls Group, he has addressed BACnet network security,

utility interactions, and communication of building data to emergency responders. He is a member of ASHRAE.