Novel Integrated Energy Systems and Control Methods with Economic Analysis for Integrated Community Based Energy Systems

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***Abstract*--A framework for establishing neighborhood based Integrated Energy Systems, which are highly but not solely dependant on renewable energy is presented. Integrated energy systems is a whole system concept. It includes knowledge, design, analysis, construction, and long term utilization of a community's electrical, mechanical, thermal, educational, and governing systems at all levels, individual homes, communities, local and regional infrastructures, etc. The authors depend heavily on their experiences in the USA State of Florida. The guidance should be generally applicable to world wide communities with additional considerations. Integrated energy systems will provide significant benefit to both the community and the national grid infrastructure. These systems can provide economic, ideological, and aesthetic satisfaction to certain homeowners who believe a greater dependence on renewable energies is demanded by world events. These systems also can also provide significant performance improvements for a national grid that faces rapidly increasing demand at a pace that surpasses the pace of additional transmission or even generation in some places of the world. In this paper we touch on considerations for the national infrastructure, the actual neighborhood microgrid design, the energy sources, the economic analysis and education. This is intended to be a start of discussion and not an exhaustive analysis or case for integrated energy systems.**

***Index Terms*—renewable energy, distributed control, microgrids, thermal systems, economic analysis, neighborhood design.**

I. Introduction

Robust and secure community and neighborhood based microgrids may in the future lead to hardened power systems by providing significant reliability and security benefits. However, significant integrated energy systems, along with control and economic analysis are needed at the first principles level. The science and technologies must achieve increased renewable and nonrenewable energy source utility while also increasing the expected community energy efficiency above an introductory baseline and provide sufficient stored energy at the point of common coupling for grid stabilization, islanding, power quality improvement, and many other grid management objectives. To be economically, aesthetically, and politically desirable, such a system must go beyond traditional power system of wires. The system must be designed from a novel combination of thermal management, electrical power generation, energy storage, control, and sound economic analysis, with significant assurances of long term community based response, to convince large stakeholders and gain seekers to enter the market, both as regional utilities and consortia of home owners. The energy systems that must be considered can be divided into two basic subsystems: First, fully decentralized energy centers, in which each residence has (for example) its own high efficiency HVAC unit, fuel cell stack, solar collector, and PV array, and second, a common energy center with diverse forms of energy storage and high efficiency HVAC unit, solar collectors, fuel cell system, and PV arrays. All subsystems must be under some management system capable of handling many diverse objectives, thermal management, energy conversion, energy storage, integration, control, and customer satisfaction at all levels. One must consider the integration of the different energy subsystems and their contribution to the overall system efficiency, the characterization and optimization of the integrated energy system, the determination of the optimal subunit size for energy centers that serve several users in the community, the optimal design of thermal fluids distribution and collection networks for minimum operating cost and reliability, and the cost initiatives for allowing stored community energy to be mobilized by a regional authority for grid functions at the point of common coupling.

This paper is intended to be a start of discussion and not an exhaustive analysis or case for integrated energy systems. The paper presents a framework for establishing neighborhood based integrated energy systems, which are highly but not solely dependant on renewable energy. Integrated energy systems is a whole system concept. It includes knowledge, design, analysis, construction, and long term utilization of a community's electrical, mechanical, thermal, educational, and governing systems at all levels: individual homes, communities, local and

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regional infrastructures, etc. The authors depend heavily on their experiences in the USA State of Florida. The guidance should be generally applicable to world wide communities with additional considerations. Integrated energy systems will provide significant benefit to both the community and the national grid infrastructure. It is hoped that these systems can provide long term economic, ideological, and aesthetic satisfaction to certain homeowners who believe a greater dependence on renewable energies is demanded by world events. These systems also can also provide significant performance improvements for a national grid that faces rapidly increasing demand at a pace that surpasses the pace of additional transmission or even generation in some places of the world. In this paper we touch on considerations for the national infrastructure, the actual neighborhood microgrid design, the energy sources, the economic analysis and education.

II. BACKGROUND FROM THE STATE OF FLORIDA

In many ways, Florida has become a leader in the development of planned communities to address issues of urban sprawl while improving quality of life for its residents, through a design mantra now known as "new urbanism." [1] Meanwhile and as seen in Fig. 1, Florida is growing at a rate of over 1000 new residents per day and is projected to overtake New York as the Nation's third most populous state before 2015.[2] Florida's electric power demand is projected to grow by over 10 GW over the next 10 years. Less than 2% of the 2006 electrical generation capacity comes from renewable resources, including municipal solid waste. Excluding municipal solid waste, electric power from renewable resources drops to ¼ of 1% of the total capacity. And the total percentage from renewables is actually projected to decline over the next 10 years without proactive steps to chart a new course.[3] This paper offers a framework for a new approach that, if successful and deployed on a large scale, could take a major step towards measurable increased use of renewable energy resources in Florida and elsewhere in the US.

Florida is not a heavily industrialized state. Over 90% of electric power in Florida is for commercial and residential use, versus 59% and 72% for neighboring states, Alabama and Georgia, respectively.[4] So, particularly in Florida, a tremendous opportunity exists to reduce reliance on fossil energy through increased use of renewables by incorporating renewable energy resources into the design of new communities, especially "new urban" designs, that seek a harmonious integration of the architecture, landscape, land use, water, and, importantly, energy. While a great deal of progress has been made in evolving "new urban" design concepts to address the human, social, environmental and overall quality of life issues, little work has been done to address integration of renewable and sustainable energy systems into the community design.

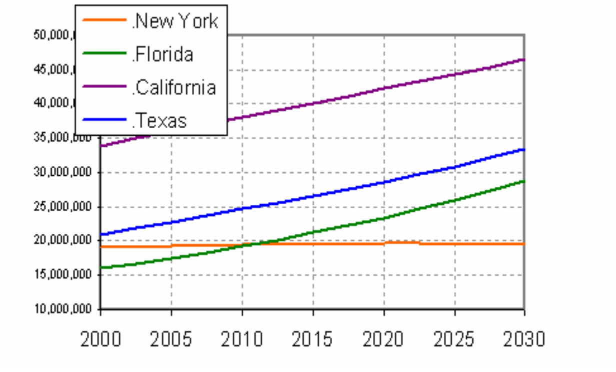

Fig. 1 Four Largest State Population Growth Rates

III. MICROGRIDS AND THE NATION'S ELECTRIC POWER INFRASTRUCTURE

The US wishes to increase the robustness and efficiency of the nation's electric power infrastructure. One way to do it, at least conceptually, is to replace large power plants with small power plants or microgrid resources. The U.S. Department of Energy wants to increase the use of microsources (sources of 200kW or less) arranged in microgrids, cooperative enclaves of microsources and power users. [5] The impact of individual failures would be reduced and power sources could be closer to usage points. This would reduce transmission losses and take pressure off the transmission grid, which cannot keep pace with growing generation and consumption.

Replacing one percent of the one million megawatts of nameplate capacity in U.S. service in 2004 [6] would require on the order of 50,000 new 200kW generators, three times the 16,700 active U.S. generating units. While such an increase would not in and of itself force automation—there are many small sources in operation today—it is difficult to imagine widespread deployment without automating day-to-day operations and response to at least simple contingencies. Power system resources need to be operated and managed by a distributed system of responsive entities that allocate resources, negotiate trades, share workload, provide redundancy, and maintain cybersecurity through mutual observation. Today's increasingly dangerous cyberclimate precludes any means that is not very secure in the cyberdomain. The ability of an automated system to provide cybersecurity is a broad topic. [7], [8], [9]

A power system is a set of sources, loads, and interconnections such that any of the loads can be at least partially supplied by any of the sources. Breakers and switches govern the interconnection of these elements. Generally, power systems are designed such that peak system load can be satisfied by system sources, but this is not implied by the definition.

Power system operation consists in producing, transmitting, and distributing power, meanwhile minimizing the negative effects of failures and other unexpected events. Power system management consists in determining which sources are to produce power, what their set points are, and which loads are to be satisfied, and maintaining all transmission lines at or below thermal limits. When depending on renewable sources of energy requires a substantial investment in energy storage. As a Florida integrated energy systems example, with today's solar technology one can expect roughly 120KW/acre peak generation from solar at local apparent noon on a sunny day (for possibly a total of 300KW/Hr) and you can also foresee a need for 3-4 KW/home peak shaving capacity (for possibly 6KW/Hr). These numbers are just an author's estimate and don't reflect a study. Unfortunately, this peak shaving is needed in mid afternoon during the summer and slightly after midnight on the coldest nights of the year. Additionally, if the electric power infrastructure needs access to this energy for local voltage support or power quality mitigation overall control of the energy storage needs to be shared with the local and regional control rooms.

For the national resources, the ability to make and implement coordinated, precise management decisions quickly can make the difference between continued operation and going dark. If community based microgrids are to make a significant impact on the national infrastructure's robustness, they must have sufficient generation capacity to supply loads for a significantly larger geographical footprint than the community itself. This is to support islanding. Islanding is the division of a power system into two separate power systems, the smaller of which is the island. The power system definition implies that when either the source or the load of a transmission path does not lie within the island, the source will not be able to provide power to the load after the transition. It is possible that island sources will not be able to satisfy island load at pre island levels. [10,11]

Thus if we are to look to the future of a national grid supported by community based integrated energy systems, significant and in excess energy storage and generation must be required of communities wishing to *go renewable*. Proper encouraging economic incentives need to be given to developers and homeowners, such as subsidies and allowing sufficient economies of scale in service support, hydrogen, natural gas, fuel oil, etc. Additionally, structures need to be allowed that will allow these communities deal equitably with the corporate and municipal entities that they are connected.

The IEEE is currently addressing many of these concerns in the Working Group P1547, Standard for Distributed Resources Interconnected with Electric Power Systems.

IV. RESIDENTIAL MICROGRID MODELING AND CONTROL

A residential microgrid provides reliable emergency backup power to the homeowners of a residential development during times of extended power interruptions resulting from storm damages or other related causes. Currently the only alternative to the electric utility in periods of prolonged outages such as following hurricanes is the individual home generator. Such home generators, particularly gasoline engine generators, are wasteful, expensive, and potentially dangerous to the homeowner as well as personnel of the electric utility.

Currently, home developers have only the home generator option to offer emergency backup power generation to the prospective purchaser of a new home. The cost of a generator including a utility approved manual transfer switch, wiring, controls and fuel tank approaches $10,000 to $15,000. The homeowner is also required to provide routine maintenance, periodic starting and testing, and maintain the fuel integrity. If routine maintenance and testing are not performed the emergency generator is likely not going to start when called upon. In contrast to the individual home generator approach, consider the concept of a neighborhood microgrid.

Collection of industry data to develop a Residential Microgrid Model (RMM) is underway to demonstrate the feasibility of a Residential Microgrid System. Two main types of data are being used for the RMM. The first is the residential development data obtained from Centex Homes. [12] The development is Cypress Trace located in southern Duval County. This Centex development is adjacent to Nocatee [13], a master planned development with expected population of 35,000 over the next 20 years. A challenging unique aspect of this area of Florida is that it is on the end of the transmission lines of both JEA [14] and Florida Power and Light. [15] Centex is also planning additional communities in Nocatee as are other residential developers. The second focus area for industry data is to obtain representative data from the electric utility, JEA in this case, regarding power distribution to the RMM community. Cypress Trace electricity is supplied by JEA.

Cypress Trace is a modern home development consisting of approximately 250 homes averaging 2,000 to 3,000 square feet in a new planned community. The homes are constructed according to the latest standards, both for structural integrity to withstand storms as well as a high level of energy efficiency. JEA has designed and layout of the distribution feeders, interconnection fuses and switches during the planning stages of the development. The purpose of the Residential Microgrid System includes installation of a cost-effective, safe, reliable and dependable system. This provides the homeowner a smooth, safe transition from regular service to emergency power in the event of an extended interruption, even if not home. It also provides cost savings, both capital and operating, over individual home generators, ensures safety to the homeowner by not handling fuel, avoids improper interconnection with the utility, and avoids exhaust hazards from internal combustion engines. This ensures safety to the electric utility workers to perform power restoration duties without the danger of electric shock from improperly connected emergency generators.

The Residential Microgrid System consists of a common generation facility, protective relays, controls, and monitoring all to meet the utility interconnection requirements. [16,17,18] The system is being modeled using the MATLAB/Simulink SimPowerSystems toolbox. [19] The generation facility consists of a set of diesel turbine generators. It is designed to be located on the common areas of the development and interconnects with the underground distribution system of the utility. The generation facility could actually be built by the developer, pro-rated on a "per lot" basis for approximately one-half the cost of individual generators, and the ownership turned over to the utility in a manner similar to the other infrastructure of the development. Advantages of such a neighborhood generation system include added value to the community. The distributed microgrid system increases marketability of the subdivision. The set of generators correctly sized to supply the subdivision instead of one unit per residence, is as low as one-half the cost of individual home units. One strategically located central building for the generators and their controls is located away from the individual residences. This generator building can be architecturally treated to blend in with the other structures in the subdivision.

The system connects at the main feeder from the utility and ties into the underground distribution system to the individual homes in a manner approved by the utility. As the subdivision grows additional generation of various types can be strategically added to accommodate phased community expansion. In the event of a power outage, the system provides emergency backup power automatically to the homeowners in a smooth, safe transition. The homeowners are not required to do anything but wait for the system to start. The homeowners' association fees will include the cost of operating and maintaining the emergency backup power service. The distributed microgrid reduces the need to vacate the residence during the emergency. If the homeowner chooses evacuation, the emergency backup system starts automatically, so the critical home electrical systems will be functional. The system is designed to enable the owner to maintain current lifestyle and comfort – virtually eliminating stress associated with power interruptions.

The distributed microgrid eliminates the need for the individual homeowner to be concerned with any aspect of owning an emergency generator. Maintenance and/or repairs will be performed by professionals. There are no requirements for storage of fuel or lubricants at each residence and there is no concern for noise or vibration or exhaust fumes at the residences. The distributed micro-grid system minimizes the environmental impact. Fewer, larger generators are more efficient than hundreds of smaller units, therefore emitting fewer pollutants.

Although the residential micro-grid concept poses some technical, legal, and regulatory issues that will require understanding and collaboration among the developer, homeowners, and the electric utility, there are distinct advantages of the micro-grid system to the utility. The possibility of inadvertently energizing the utility's distribution network is eliminated. Because criticality of power restoration is reduced, the micro-grid enables the utility to safely restore power at a lower priority; this potentially eliminates the need for line crews to perform repairs during periods of dangerous storm conditions (high winds, lightning storms). The utility will be able to remotely monitor the status of the system through the utility control and monitoring system.

There are currently two main scenarios being considered for the RMM to demonstrate the feasibility and benefits of the Residential Microgrid System using the modeling and simulation efforts. The first and primary scenario is the outage due to catastrophic event such as a hurricane. The second is the use of the system to supplement the power distribution of the utility. As mentioned above, the subdivision under investigation is on the distribution end of the utility transmission feeder lines. An additional resource would likely benefit the utility on extreme hot weather days. The distributed microgrid could be remotely dispatched by the utility for peak shaving and load balancing. Therefore, some level of supplemental power from the Residential Microgrid System can be made to the electric utility to be used elsewhere in the distribution system.

Note that in these state-of-the-art community based microgrids are based on an old design paradigm, you are either *on the grid* or you are *on the backup*. There are many reasons for this. Many are economic or regulatory and some crucial reasons concern system control and stability. All of these reasons are beyond the scope of this paper. Suffice it to say that in the, hopefully near, future we will be building and living with systems that act in parallel with the grid as an integrated energy system.

V. RENEWABLE ENERGY SOURCES AND STORAGE - ANALYSIS AND DESIGN

The energy systems that need to be considered in this future can be divided into two basic categories: First, the top level fully decentralized energy centers, in which each residence has (for example) its own high efficiency HVAC unit, fuel cell stack, solar collector, and PV array, and second, the alternative of having a set of residences sharing a common energy center with high efficiency HVAC unit, solar collectors, fuel cell system, and PV arrays. Both alternatives present design challenges associated with the selection, thermal management, integration, and control. Study still needs to be done for the integration of the different energy subsystems and their contribution to the overall whole system efficiency, the characterization and optimization of the integrated energy system, the determination of the optimal subunit size for energy centers that serve several users in the community, the optimal design of thermal fluids distribution and collection networks [20] for minimum operating cost and reliability.

Integrated energy systems will come about from an integrative design philosophy [21] in which the energy system can be conceived from the beginning as a system designed to perform certain global objectives optimally, not as an ensemble of already existing parts. In the thermal optimization of the different components (e.g., fuel cells [22, 23], heat exchangers [21], energy storage units) all must make use of the thermodynamic optimization methodology [21] to identify the ways (features, procedures) by which the system fulfills its functions while performing at the highest thermodynamic level possible.

Considerations during design and analysis include:

1. Minimizing electrical energy and demand requirements – advanced design and technology integration will be deployed to minimize electrical loads and demand in homes and in the community. Load factors will be maximized using supervisory systems to balance supply and demand resources.
2. Providing common hot and cold supply loops to minimize community cost of service – best available commercial technology will be deployed that will significantly reduce the energy and demand requirements and costs to heat and cool the community. Ice storage will be investigated as a method to shave peak loading and fill valleys to maximize load factor.
3. Using photovoltaic roofing systems and local energy storage to supply incremental energy needs for homes – PV roofing shingles will be used to maximize exposed solar surfaces while conforming to the architectural design aesthetic.
4. Using composting toilets and localized gray water treatments to eliminate need for community wastewater treatment facility – water management will be done locally using environmental friendly techniques.
5. Evaluating other renewable energy resources available to support community infrastructure – wind, water, solar, biomass, thermal, and other renewable resources will be evaluated to determine the best available renewable technologies that will support the community needs.

6. Integrating fluid systems into the community wide energy management scheme. Water/wastewater treatment poses significant opportunity for efficient energy management since exothermic and endothermic reactions are taking place which can provide significant energy source, utilization, and storage.

VI. ECONOMIC IMPACT AND ANALYSIS

Developers often connote green development or "new urbanism," with reduced profits and delayed schedules. Conversely, according to the Rocky Mountain Institute, green development projects often "perform" extremely well financially, and direct a price premium in the marketplace. Benefits include lower operating costs for residents, increased comfort, higher perceived value, reduced sprawl and protection of the natural environment. Successful examples of green development include: cluster development, minimum disturbance, site fingerprinting, greenbelts, greenways, and trails, woodland conservation, transition zones, wildlife corridors, stream buffers, and streambank stabilization techniques. These criteria need to be considered in the overall initial site development for integrated energy systems.

Thermoeconomics,which combines methodologies of exergy analysis [24, 25, 26] and economics for optimizing the design and operation of thermal systems, should be employed in the design of these new community based energy systems. A typical example of systems suitable for thermoeconomic analysis are power generation units. In plant design, for example, mass, energy and exergy flowsheets are generated; cost estimates are associated to the streams, and equipments and the plant can then be designed, accounting for both thermal and economic aspects of it.

HVAC and energy systems play a large role in building energy efficiency and occupant comfort and productivity. Within high performance buildings, these systems must perform much better than typical systems in every aspect: construction costs, energy, maintenance, and comfort. High performance HVAC systems should have performance goals for net zero energy consumption—or better—and must be designed to require the minimum of materials for life-cycle installation, modifications, and alterations.

Demand costs are the main consideration in determining the economics of a thermal design system. Energy savings may be achieved, particularly in new construction or major renovation projects, but typically are a small percentage of operating cost savings. In fact, energy consumption may increase and still allow for an economically viable project. To determine economic feasibility, accurate heating/cooling load data from the existing heater/chiller unit is always best. Available data, even for a short time period, can be used to help calibrate the simulated building model and improve its accuracy. For this study, data will be available for the entire project timeline.

A developer must estimate demand savings from thermal energy storage systems and program these economic savings into the design. The time period when the energy is consumed has a significant impact; i.e. on-peak demand reduction or displacing expensive onpeak energy with less expensive offpeak energy use. In general, system economics depend heavily on the demand savings and/or on-peak/off-peak rate differential. Anther economic determinant to be considered is a function of the load and its shape factor. The load shape factor is a needed multiplier because peak cooling load typically is not constant. This factor is for the on-peak period only (the time when heating/cooling load will be shifted) and for the peak heating/cooling load for that day. Typical load shape factors are in the range of 60 to 90 percent for a variety of building types and climates. Annual energy shifted is the sum of daily energy shifted. At this point, an estimate can be made using an average heating/cooling load for each month and the number of cooling days in the month, then summing the monthly totals. Additional economic factors to examine with respect to thermal design include: Floor Height, Electrical Capacity, Useable Space, and Operation and Maintenance Requirements.

The economic analysis needs to have a two-pronged approach. First, the economics/energy costs of the various thermal design system scenarios need to be examined and reported. Second, the economic impact of this study's new growth model will be reported on a local (county) and state-level (Florida). The economic impact will be analyzed ranging from the initial pilot project to the entire projected built-out community at the completion of the project.

VII. COMMUNITY EDUCATION

While coming last in this paper and receiving less space, one cannot underestimate the need for community education in a successful "energy systems" based community. All stakeholders and gain seekers must build civic awareness around planning for a sustainable future. This is crucial because the economic and scientific optimizations that will be used to justify such communities will more than likely be very brittle, with high sensitivity to the long term behaviors of those actually living in and governing the communities.

Homeowners must believe that environmental projects, best home maintenance practices and sustainable building methods help to preserve the future and enhance quality of their life and that of their neighbors. The citizens of the community must have instilled in them a sense of local identity, based on a natural and cultural heritage that is not nostalgic, but bold and visionary. The school system must have curricula educating the public and its children on the principles of whole systems. Future planners, developers, and builders who inter the community late must be enabled make decisions with sufficient information regarding their impact on the original and evolving visions of the community.

The education focus needs to extend from the design of the single family home, the surrounding site development and preservation of adjacent ecological systems through the use of protective green space, restored wetlands, the protection of riparian buffers, groundwater recharge zones, and clustering development away from water resources. All of which has a direct impact on the efficiency of a truly integrated energy system community.

The community based education system needs give seminars presenting scientific discoveries from peer reviewed publications and government studies. It also needs to host a webpage with a library of technical reports, published papers, engineering and economic analysis tools, and other community interest resources concerning: energy systems, control methods, and economic analysis for integrated community based renewable energy systems.

VIII. CONCLUSIONS

Pragmatism is the order of the day with respect to integrated energy systems. Communities with integrated energy systems that depend heavily on renewable energy resources are coming. Their success depends on a sincere and programmatic understanding of not only integrated energy system benefits, but also the long term commitment requirements. These systems present significant potential benefit to consumers and suppliers alike. The State of Florida is an excellent target market for near term exploitation of these technologies and the authors are certain many other locals are as well. As these communities are cited and evolve they need to be monitored and analyzed to assure the continued appeal of their future development. Government regulation and industry standards and practice need to be modified, as has already started, if this direction is to be pursued. Certainly, the public's expectations and behaviors need to be prepared for the future success of these communities and increased renewable utilization in general. Finally, the author's are excited as these new technologies will provide long term research opportunities.

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