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Research paper

Smart Energy Systems: The Need to Incorporate Homeostatically Controlled Microgrids to the Electric Power Distribution Industry : An Electric Utilities' Perspective

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Abstract

For no one is a secret that nowadays electric power distribution systems (EPDS) are being faced with a number of challenges and concerns, which emanate not so much from a shortage of energy supply but from environmental, infrastructural and operational issues. They are required to preserve stability and continuity of operations at any time no matter what, regardless of what may occur in the surroundings. This is the true measure of what sustainable energy systems (SES) are all about and homeostaticity of energy systems seeks just that: to bring about a rapid, effective and efficient state of equilibrium between energy supply and energy expenditure in electric power systems (EPS). The paper presents the theoretical groundwork and a brief description of the model for the operation of SES and their role in energy sustainability, supported by theoretical and empirical results. The concept of homeostaticity in EPDS is explained, along with its role in SES.

Keywords: *homeostaticity; sustainable energy systems; environmental challenges; thriftiness; proactive response; reactive and predictive homeostasis.*

1. Introduction

For no one is a secret nowadays that electric power generation and distribution systems are being faced with a number of challenges and concerns, which emanate not so much from a shortage of energy supply but from environmental, infrastructural, operational and legal issues. They are required by law—as all public utilities are—to respond to such challenges and threats as transmission and distribution lines failure, transformers break-down as a result of harsh rains, hail and snow fall, violent and unanticipated winds or sudden natural disasters like what we have seen in Chile, North America and in many other places recent years. Torrential rains, fires and earthquakes are to be dealt with very rapidly and effectively so as to preserve stability and continuity of operations at any time no matter what, regardless of what may occur in the surroundings.

1.1. Towards a New Electric Utilities' Perspective

Public utilities, especially electric utilities like ENEL, know this quite well, and they are doing something about it. This in fact is the true measure of what sustainable hybrid energy systems (SHES) tied to the grid are all about, and homeostaticity in energy systems seeks just that: to enable distributed energy systems (DES) run by electric utilities like ENEL to become highly efficient, proactive and effective very rapidly under any circumstance, based on their built-in intelligence, their installed capacity and their generation and supply requirements. They do this by attaining a state of optimally efficient equilibrium (homeostaticity) between energy supply and energy expenditure in electric power systems (EPS) operation. To accomplish so they ought to imitate homeostasis mechanisms present in all living organisms. Ever since Cannon (1929, 1935) [1,2] first introduced the concept, attention on homeostasis and its applications have been the sole patrimony of medicine and biology to find cures for diseases like diabetes and obesity. Nevertheless, homeostasis is rather an engineering concept in and of itself—even more so than in the natural sciences—and its application in the design and engineering of sustainable hybrid energy systems (SHES) is a reality with the outlook of incorporating DES to the utility grid. Thus homeostasis mechanisms are present in all living organisms, and as such are also applicable to EPS engineering in order to enable and maintain a sustainable performance when they are linked to energy efficiency (EE) and thriftiness. In doing so, both reactive and predictive homeostasis play a substantive role in the engineering of such mechanisms [3,4]. Reactive homeostasis (RH) is an immediate response of the SES to a homeostatic challenge such as energy deprivation, energy shortage or imbalance. RH entails feedback mechanisms that allow for reactive compensation, reestablishing homeostasis or efficient equilibrium in the system. Predictive homeostasis (PH), on the other hand, is a proactive mechanism that anticipates events that are likely to occur, sending the right signals to the central controller, enabling SES to respond early and proactively to environmental challenges and systems' concerns [3,4]. Therefore, based on the above arguments, it is reasonable to expect that government authorities as well as legislators and industry pundits do something about it with the degree of responsibility shown elsewhere in the world, as for example in North America [5,6,7]. It is time that those responsible for these issues affecting electricity transmission and distribution, like the Superintendencia de Electricidad y Combustible, SEC in Chile or the Agencia Nacional de Energía Eléctrica in Brazil take action, instead of just worrying about the problem as we wait for the next outage; in regards to having critical outposts such as hospitals, airports, emergency health-care units, residential areas and transport systems being equipped with a fully functional, powerful and ready-to-go microgrid that can be incorporated in the electricity distribution grid [8,9,10]. We know that we need a new solution to an old problem: the vulnerability and feebleness of our current EPS infrastructure, especially in the distribution sector. That solution comes in the form of a smart distributed generation (SDG) solution like the microgrid. One that is connected to the grid, and that includes both solar photovoltaic and thermal energy sources, as well as wind generation where available and possibly energy storage for critical processes if necessary [3]. This could greatly minimize the impact on such critical services and other equally important ones as well, in case urban areas like Santiago de Chile were to suffer another power outage as in the past [11,12]. Unfortunately, however, at present there are no incentives in place in Latin America to encourage electric utilities like ENEL to pursue microgrids. Moreover, no guarantee exists that industry regulators like the SEC in Chile, will allow the utility to recover the capital costs of the microgrid through rates as being discussed in North America [13,14].

In Chile, in particular, the matter is not even being discussed in terms of cost recovery options for investors, arguing that customers are already paying enough in their rate structure to cover for energy security, and therefore the utility should provide such security in spite of the high costs involved. A dismal outlook if one is to review the huge losses and hefty fines that they have had to face in recent years due to environmental and natural disasters. Of course, one would expect that specific critical customers in the private sector such as private hospitals and clinics and private airports should pay an additional rate fee for getting such energy security, while public service customers like the electric underground mass transport system (subway) should be subsidized by the government, and in part also absorbed by the utility. Today, thanks to Net Billing Law 20,571 for Distributed Generation of electricity in Chile, there is an alternative [15]. The law grants the right to customers of electric power utilities like ENEL Distribution, to generate their own electrical energy, self-consume and inject their surplus into the network. Thanks to this and to lowering costs of solar and wind energy generation technologies, the installation of renewable energy sources by independent clients or residential communities connected to the power distribution grid is growing, together with the introduction of some Smart Grid initiatives, as for example: ENEL's smart metering unit offering several services [16,17]. However, as it is usually the case, legislation does not move at the same pace as the market sector, and much less so as than the rate at which society's needs grow. Therefore, this new scenario is presenting new and complex challenges to utility operators like ENEL, which see private enterprises encroaching into an until very recently protected market turf. Such challenges are two-fold. They come mainly from a regulatory but also from a competition view point. Hence, in this article we present a hypothetical case being considered by ENEL of a community belonging to an average residential building, as the subject of study in upper-side neighborhood of Santiago, Chile. The community is considering the installation of a photovoltaic (PV) energy generation microgrid, with and without energy storage unit to supply electricity to 60 apartments of various sizes and consumption (referred to as a "sustainable block"). Under this scenario, a set of strategies for the coordination and supervisory control through energy homeostasis is considered [18-22], adapted for specific needs and consumption characteristics of the customers as well as of the power infrastructure of the distribution network. These are to be applied with the objective of efficiently managing the supply and consumption of energy and power in the residential community maintaining systems homeostaticity. The proposed supervisory control is designed based on homeostatic control of EPS and simulations results can be seen in [9,10,19,20] under different scenarios and with various operational options.

The paper addresses these and other important concepts, particularly homeostasis of energy systems as well as the design and engineering of what we have termed **homeostaticity** in SHES like grid-tied microgrids which is a current concept being considered by utilities like ENEL to complement their electric power distribution services. In doing so we employ material and arguments from previous work which are further elaborated plus new material is being presented also in order to advance the research in the field of homeostatic control applied to electric power systems. Hence section one serves as introduction where the main issues and arguments are laid out, emphasizing the need for SES incorporated to the electricity distribution grid in light of climate change and the need for energy resilience. This section also underlines the hurdles of electric power systems (EPS) decentralization and the roadblocks for adopting SHES like the microgrid concept. Section two elaborates on the current shift in microgrid trends from an alternative energy generation solution to a more active power industry player. A reality that although timidly moving forward is no doubt a much needed shift in the current energy matrix of countries like Chile and others especially hit by environmental and natural disasters. It also points to the need to incorporate homeostasis-based control systems in the design of SHES tied to the grid for ensuring optimal power and energy management control of such systems. Section three shows brief experimental results. Section four offers a discussion. Conclusions come afterwards.

1.2. How Homeostaticity of Energy Systems Works and Why Electric Utilities Need It.

Today's electrical energy generation and distribution systems are being faced with a number of challenges and concerns which emanate from both environmental as well as operational issues. Therefore, they are required to respond to such challenges very rapidly and effectively so as to preserve stability and continuity of operations. This is the true measure of what sustainable energy systems (SES) are all about and homeostaticity of energy systems seeks just that: to bring about a rapid, highly effective and efficient state of equilibrium between energy supply and energy expenditure in electric power systems (EPS) [3,4]. To accomplish so they ought to imitate homeostasis mechanisms present in all living organisms. Homeostasis and its applications have been the sole patrimony of medicine and biology for several decades in order to find cures for diseases like diabetes and obesity. Nevertheless, homeostasis is rather an engineering concept in its very essence—even more so than in the natural sciences—and its application in designing and engineering sustainable hybrid energy systems (SHES) is what we term homeostaticity. In this paper we present the groundwork behind the theory and offer a prescriptive model for the operation of SHES which is supported by the theoretical and empirical results. The work presented explains how the engineering of homeostaticity in SES is done and how reactive and predictive homeostasis play a key role in this system dynamics. Reactive homeostasis (RH) is an immediate response of the system to a homeostatic challenge such as energy deprivation, shortage or an energy imbalance. RH entails a feedback mechanism that allows for reactive compensation, reestablishing homeostasis or efficient equilibrium in the system. Predictive homeostasis (PH), on the other hand, anticipates the events that are likely to occur, enabling SES to respond early and proactively to environmental challenges and concerns by foreseeing when these are most likely to occur, adjusting their energy management to maintain sustainability. Environmental challenges like natural disasters and hazardous climatic events are becoming more severe and recurrent in many parts of the world, and they are here to stay, affecting millions. Nowhere is the matter being taken more seriously than in the United States where the US Senate passed a bill that supports grid-connected hybrid microgrids to tackle, among others, the issue of electric power grid readiness and resilience [5,6]. Such initiative is one of several pieces of legislation that are being studied by industry stakeholders, legislators, and also local and federal authorities in North America, to promote a range of technologies and policies that can make the grid more reliable and cyber-secure in the US and Canada. All these steps fall, in one way or another, on the path set forth by President Obama in 2013, when he introduced the Energy Independence Roadmap for the country [23]. However, the pace towards more concrete and expedient changes has somehow sped up even more, following the catastrophic natural disasters that the country has had to endure in recent years [24-27]. Among such initiatives are grants, microgrid technologies' demonstration projects and a variety of studies to determine the costs involved and to define the precise scope of action in order to shape federal microgrid policy in the immediate future [28-34]. The Energy Policy Modernization Act of 2015 [35,36] was introduced in the US Senate on September 2015. This bill amends the Energy Conservation and Production Act, the Energy Policy and Conservation Act (EPCA), and the Energy Independence and Security Act of 2007 with respect to energy efficiency in buildings and appliances. The EPCA is amended regarding the Strategic Petroleum Reserve as well. All of the above has heightened the federal role of supporting microgrids integration to the current EPS' infrastructure, something which has been largely a state endeavor to date [36-38]. In North America, for example, large-scale power outages spanning extended urban areas are not new. Still fresh in people's memory is Hurricane Sandy, known as 'Superstorm Sandy'. This natural event was the deadliest and most destructive hurricane of the 2012 Atlantic hurricane season, and the second-costliest hurricane in United States history [24-26], with damages estimated to be over $75 billion (2012 USD), a total surpassed only by Hurricane Katrina [27]. This monstrous calamity caused unprecedented infrastructure damages including major power outages. Yet there were other power disruptions as predecessors of Sandy, among them the Northeast Blackout of 2003, Hurricanes Katrina and Rita in 2005 and Hurricane Irene and the Northeast's freak Halloween snowstorm in 2011[4,39]. After each of these events, more consensuses were built among public opinion and industry leaders. Both local authorities and power industry experts were in accord that something new had to be done fast to strengthen the power distribution grid against such recurrent catastrophes. The problem lies in where to start and how much to spend, this in light of other equally pressing needs that demand attention and resources, aside from the regulatory issue which has proven quite stiff [4]. Nevertheless, on September 2014 the Clean Energy Group presented its report: "Resilient Power: Evolution of a New Clean Energy Strategy to Meet Severe Weather Threat" [40], which marked a turning point on this issue and provided a roadmap for states like New Jersey, New York and Connecticut to begin a new era of development in the fight against severe environmental challenges. Nevertheless, much work needs yet to be done going forward in North America and also in South America in order to understand the dimensions of the challenges we are facing and how the influence of extreme weather, natural disasters and all of what climate change has in store for us will have an impact on the resilience of power systems. We need to seriously study what are the possible mitigation strategies at hand and what are the legislative changes needed to enable such industry change therein [3,4,41,42]. Hence in this context the paper presents a prescriptive energy management and homeostatic control model for incorporating microgrids in residential and commercial buildings serviced by ENEL Distribucion, part of ENEL, the largest electric utility in Chile. The work presented is part of an ongoing research program funded by CONICYT of Chile under the auspice of ENEL.

1.3. Climate Change and the Current Energy Transition: Building the Case for Homeostaticity of Sustainable Hybrid Energy Systems (SHES).

Like the US, Chile is no stranger to these scenarios either, and has had its share of disasters too. The country is 'sitting on a hot stove' so to speak, with earthquakes, volcano eruptions, and rain floods becoming increasingly present in the collective consciousness of its people. Such events are simply not uncommon but are becoming prevalent not only in Chile but in many parts of the world, with climate change and harsher weather on the rise. The difference is that in today's 21st century world, much of the fragile living systems and economic sustainability depend on modern utilities' infrastructure of which roads, water, electric power transmission and distribution networks, and telecommunications are a vital part, yet increasingly vulnerable when faced with such phenomena [3,4,8,10]. On September 17, 2015 a powerful 8.3-magnitude earthquake struck off Chile's coast causing havoc and chaos in an otherwise tranquil Wednesday afternoon [11,12,43]. Unlike its predecessor of 2010, the natural disaster triggered an immediate tsunami alert and coastal evacuations were readily executed yet utility infrastructure was compromised, particularly electricity. The tremendous earthquake that struck Chile in 2010 was much worse and found the country largely unprepared. It occurred on February 27, 2010 at 3:34 AM, off the coast of south-central Chile, taking everyone by surprise. The 8.8 magnitude earthquake had its epicenter some 200 miles (325 km) southwest of the country's capital, Santiago, causing widespread damage on land and initiating a tsunami that devastated some coastal areas of the country. Together, the earthquake and tsunami were responsible for more than 500 deaths and caused major damage to infrastructure [12]. Yet, despite these and other natural disasters, the country remains largely unprepared against massive telecomm and electric power systems brake-down [4]. The problem lies in the high percentage of centralized electric power and communication systems—a model than once proved efficient and secure but which no longer holds—as well as the lack of adequate technologies and back-up/ emergency power systems for disaster recovery, something that even extends to the armed forces today. There is no energy sustainability roadmap for the country whatsoever and environmental policy is also weak and short sighted [4]. Nowhere is this more evident than when one analyzes the flaws that are built into the very fabric of our presently centralized power systems, which were on full display in the aftermath of the Feb. 27th, 2010 earthquake in Chile [12]. It is never more evident that hugely centralized power generation and distribution systems are extremely vulnerable and ineffective to disruptions from natural disasters, human error or other calamities than in a situation like this. The large power and telecommunication networks that once proved very efficient and secure, are now at the center of discussion fueling the need for decentralization and the rapid growth of distributed generation (DG). Hence it makes sense to follow other nations example seeking more decentralized, diversified and Distributed Generation (DG)-oriented energy matrix, a solution that is notoriously much better suited to withstand these disasters [44-51].

1.4. The Hurdles and Roadblocks of Electric Power Systems' Decentralization: Is it Time for Electric Utilities to Adopt SHES?

The saying is clear: a chain is only as strong as its weakest link, where the weakest link, figuratively speaking, applies to a system's characteristic or technical feature that makes it quite vulnerable in terms of its design, rather than the link of an actual chain [3,4]. Due to its geography, utility infrastructure design and operational conditions, Chile is a country that is quite susceptible to be struck by natural disasters including landslides, floods and earthquakes which can seriously impair utilities' infrastructure such as electricity, water and gas, let along roads and transportation [3,4,8]. Such events can cause major damage, producing havoc and mayhem all around, compromising the operation of key infrastructure like the power grid. Therefore, there is a clear need—as it has been already understood and acted upon in North America—to develop better, more resilient and robust approaches to enable today's EPS infrastructure to successfully withstand and overcome such adverse conditions [28-36].

The weakest link in the case of Chile's electric power distribution system is its inability to adequately sort out these events, as it was designed for normal conditions, without the level of stress and severity being imposed on the system by such scenarios [3,4]. For this very reason, DG solutions ought to be designed around the idea of flexibility, resourcefulness and energy independence, all common features of distributed control systems. These solutions may take several forms, sometimes with autonomous control coexisting with other forms of control like the traditional centralized control, but they all point to the same goal [18,22]. This way, if a sudden power failure were to occur, like a distribution line being brought down or a power transformer being lost as a result of large violent lightning storm or wind gusts, the result would be widespread shutdown [3,4,8,10]. A utility service supply disruption would impact an entire region, with long periods of limited or no electricity or water for the population until the damaged is repaired and service is brought back up again.

While the nuclear energy issue is still a double edged knife, with its pros and cons in today's electricity generation market, it is off track when it comes to energy matrix modernization and rather antagonistic when it comes to DG and renewables-based sustainable energy world trend. Nuclear energy plants can have disastrous implications to humanity should an accident or negligent act occur again (like the disasters as a result of the Fukushima nuclear power plant accident in Japan or the Chernobyl nuclear power plant meltdown in the old Soviet Union). Although still relevant to energy sustainability and security, the nuclear power issue and its future standing in today's world energy matrix is a case of profound implications on its own right, and would therefore require an entire paper to discuss it. Yet if we are to focus too much on power generation technologies like nuclear, fossil fuels or hydroelectricity generation, we may be missing the larger picture or at least not giving it its proper place in the scale of concern it deserves [4].

Although economically efficient, traditional centralized EPS (including nuclear energy) are not only vulnerable in regards to natural disasters and other environmental challenges that may threaten our energy supply, presenting very little flexibility and no diversification of energy sources [3,4]. There is also the vulnerability of EPS infrastructure and how its collateral damage in case of collapse can manifest itself in a variety of forms, like the still huge concentration on fossil, non-renewable fuels, the need for safe and steady fuel provisioning, and large hydroelectric projects which require building large dams, inundating vast extensions of fertile land [10].

Centralized electric power generation and distribution systems as well as large telecommunication networks have, on the one hand, large economies of scale and are very efficient, especially when it comes to serving large interconnected metropolitan areas, as in North America for example, but that comes at a cost. Their major drawback and weakness however are quite evident and alarming when large power black-outs occur (Chile has had several in the last few years) which leave large populated areas in complete and utter darkness, sometimes for several hours, causing widespread chaos, mayhem and rampant looting all around [10,4]. Their sheer size and highly centralized architecture makes them extremely vulnerable to natural disasters and major accidents due in large part to human error. In this way all the economic gains as a result of high efficiencies, power quality and stability achieved by creating these huge electric power grids are all of a sudden lost when a disaster like Hurricane Sandy or a major earthquake strikes. Centralized EPS are concentrated usually on a few, very large power plants, operating on thermal and hydroelectricity generation for the most part, and distributing power in a radial-type distribution scheme, with each substation supplying electric power to radially-connected nearby communities [52,53]. They provide service across a wide range of consumers over vast distances that span hundreds and even thousands of miles, all of which increases the risk of disruption dramatically (generation and distribution power topologies) [4].

Hence, the sheer forces involved in just about any natural disaster (whether it is a storm bringing strong winds and snow, flood waters, violent quakes or volcanic eruptions) are no match when it comes to our presently centralized power systems, especially in the case of the two most vulnerable parts of any power system: transmission and distribution. As an example, just one afternoon of strong winds, although rare in the Santiago metropolitan area, can knock dozens of trees and blow away roof tops, disrupting electricity distribution to several areas at once, with fallen trees over power lines, damaged transformers, and other similar havoc that can deprive whole metropolitan areas of power for several hours [3,4]. All of these are strong arguments in favor of decentralization of power systems and the need for more rapid advancements in DG penetration in the form of SES [54-59]. Hopefully, adequate legislation initiatives will be more forthcoming in the years to come, bringing changes that can make possible the transition to a more secure, robust, resilient and better prepared EPS come to fruition [4].

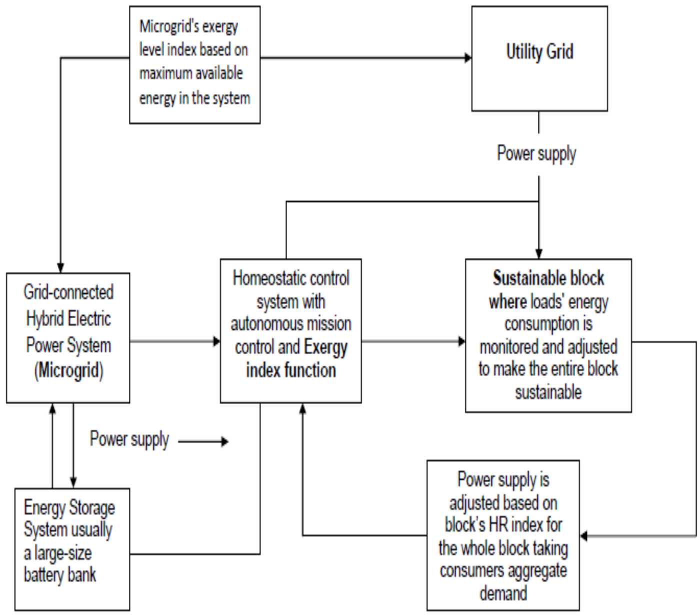

Fig.1. A particular example of the homeostatic control (HC) model for SHES. Here both energy and exergy management are built in the SHES to enable resilience and sustainability [10,18,19,21,22]. Source: owned elaboration

2. The shift in microgrid trends, from an alternative energy generation solution to a more active power industry player.

While DG solutions like the microgrid or diesel generator sets were first thought as an alternative solution for remote and isolated areas only, as back-up in case of a power outage, or because grid power was unreliable or simply non-existent, like in many parts of Canada and other places in the world where no transmission lines exist, that is no longer the case [8,9,10,4]. Yet in many places in Latin America and elsewhere in the world there are still a number of rural and semi-rural areas with weak or no connection to the main grid. Thus microgrids are becoming increasingly more relevant and viable as a solution to both urban and rural areas of all sizes and configurations and are now being considered by electric utilities, just like in North America. Microgrids are first and foremost local DG solutions that comprise a number of feeders (one or more), servicing a clusters of loads not necessarily grouped together. Some of these loads are more sensitive while others are considered less or non-sensitive, therefore the microgrid system's design and configuration, including the choice of control system, is in part dependent on the role of the microgrid itself, the energy sources employed, and the nature and size of the loads to be serviced [4,10]. In order to operate autonomously or semi-autonomously so as to reliably supply electricity and heat to a local community whether urban or rural for example, the microgrid may or may not have energy storage systems, depending on budget and system's operation necessities, and may operate connected to the grid if need be and conditions allow so or operate as a stand-alone system [8-10,18-22]. The degree of resiliency and robustness of the microgrid itself is given by the choice of engineering design and configuration characteristics, both of which depend on technical and budget constraints. Such aspects will influence how much the microgrid, and any other form of DG for that matter, will be prepared to act as a potential solution to endure adverse environmental conditions, while continuing to provide service following a natural disaster or harsh climatic event. Also the question of how microgrids can be designed in a way that can be incrementally integrated to the current EPS will depend on adequate legislation like the net billing law passed in October 2014 in Chile [15] as well as finding the right business and operational architectures that can accommodate these new market solutions. Thus, in light of the current necessities and changing industry trends, alliances involving communities, power utilities and independent local operators are likely to emerge [48-53], just like it has occurred in North America, with notable examples in the US and Canada as well as in the UK and other parts of Europe [3,4].

The interesting Smart Grid concept of energy hubs [54,56] built around the current EPS infrastructure is an idea that is being explored in Chile at present, where such localized energy hubs could be built around residential and commercial clusters incrementally, provided that adequate legislation and industry incentives are forthcoming in order to transition to a new EPS reality. This is needed in order to break away with the old unfit paradigm of today's power long distance transmission and distribution networks [10,55,57]. SHES not only will keep the lights on and basic services running for the residential and critical facilities' loads they serve, but can also act as a power source that can aid the grid in times of trouble. Microgrids constitute a fundamental resource as well as an electric power industry's paradigm change, as demonstrated in New York city for example, during Hurricane Sandy, and it is at the forefront of the new energy independence (from the grid-only scenario) trend towards localized energy production and provisioning in the United States, Canada and several places in Europe as well. In fact, North America, along with several European countries and Australia, are now looking at microgrids not just as a means towards more energy independence and more resilient and robust EPS, but also as an industry game changer in the face of very pressing energy needs like we see in Chile for the years ahead. Important technological advances in power electronics and renewable energies, the falling prices of certain energy generation technologies like solar photovoltaic and some wind turbines are significant drivers. These, along with a rise in very harsh weather patterns and natural disasters like earthquakes and landslides, have accelerated this change of thinking on the part of industry agents, local authorities and legislators alike [3,4].

2.1 How to Incorporate Homeostaticity in Electric Utility-Operated Microgrids.

Since Cannon first formulated the concept of homeostasis over 80 years ago [1,2], attention has largely been focused on the corrective responses initiated after the steady state of the organism is perturbed. However, the concept of homeostasis should be extended not only to include reactive homeostasis but also the precise homeostatic control mechanisms that can be designed to enable a sustainable energy system to predict when environmental challenges are approaching or are most likely to occur [3,4]. Sustainable energy systems (SES) encompass both reactive and predictive homeostasis mechanisms operating recursively and in coordination with one another in the face of environmental challenges. Hence, the ability of the energy system to respond to such challenges rapidly and effectively so as to attain equilibrium between power supply and energy demand to preserve stability and continuity of operations is the true measure of what sustainable energy systems (SES) are all about. This set of mechanisms is what we term homeostaticity in electric power systems' operation. Reactive homeostasis (RH) in SES, as the name suggests, is a feedback-enabled mechanism driven by energy generation and supply versus consumption or expenditure of energy [10,3,4,18-22]. This can be engineered in microgrids built around the concept of SHES by employing advanced sensors, control limit actuators (for example set-point fired responses) and artificial intelligence (AI) algorithms that allow the system to make timely decisions in order to respond to changes in a predetermined set of systems control variables [3,4]. Thus SES take actions to counteract or fend off adverse conditions and noise that may affect the system's normal operation [3,4,10].

On the other hand, predictive homeostasis (PH) mechanisms generate responses well in advance of potential or possible challenges, once the system has reached a threshold signaling a predetermined degree of likelihood that an event will occur. Hence there is a set of precise SES responses that come about in anticipation of predictable environmental challenges. Such PH responses enable the energy system to immediately prepare itself, taking the necessary precautions and actions to adapt and even reconfigure itself if necessary, in order to respond to the challenge ahead of time. Such actions may come in several forms and will depend on the resources and intelligence built into the system, but they are all geared towards making the SES more secured and able to withstand the upcoming challenge by activating its readiness control mechanisms [3,4,10]. Actions may come differently in magnitude and timeliness; some may be big and come immediately to adjust parts of the SES operation while others may come in the form of smaller changes in the system, largely as a result of stage-by-stage preparedness protocol building over time. The decision of which changes will occur first, where and how big they will be will be determined by both RH and PH control mechanisms engineered in the SES. Some may come very soon while others may come a longer time in advance of a probable environmental challenge. However, as we all know, systems are prone to internal conflicts when control criteria superimpose on one another generating the wrong response [3,4,10]. Reality is not always adequately interpreted and possible challenges may not always be correctly anticipated or foreseen in their full magnitude and scope. Also misread signals and misfires may risk a wrong or inadequate response as systems sometimes experience false alarms and misfires [4]. These may occur in part as a result of possible conflicts over certain homeostatic control (HC) variables that may share common goals and values but different scope of action and logic sequence, depending on the scenario being faced. Such HC variables may involve PH and RH control logic sequences which, if inadequately engineered in the SES, may result in inadvertent clash that can hurt system's performance [3,4]. Therefore, careful engineering of such capabilities in SES must account for such conflict of interest and changing scenarios must also be accounted for when establishing set-points [9,10]. Adequate measures must be engineered in the system's design to prevent PH responses interfering with RH mechanisms. If these potential conflicts were not accounted for and swiftly overcome, should they arise in the course of events, undesirable conditions may emerge which can compromise the effectiveness of SES readiness mechanisms, risking the very sustainability and efficiency of the system itself [4].

2.2 Homeostasis-Based Power and Energy Management System for Microgrids.

In the case of PH the system responses will come as a result of information being processed by the system as the stimulus approaches and is detected by the sensing devices. Here there are both RH and PH sensors and HC software that account for an ample array of control mechanisms ready to act whenever conditions arise [4]. Thus homeostaticity of SHES requires a careful equilibrium of such control mechanisms and the coordination of internal and external decision variables—all of this as part of the particular HC strategy designed in the SHES—which will stand guard against a variety of adverse conditions and possible challenges [3,4,18-22]. Thus the SHES will control the use of its energy resources including the grid and the use of alternative energy sources like energy storage if the grid is off. It will do so recursively and permanently in order to generate and supply enough energy to meet the loads demand, while at the same time, signaling to consumers how much energy is the SHES capable of supplying [3,4,18-22]. The question of if and how much energy will go into the energy storage will be determined by the HC system based on the situational awareness and degree of criticality being experienced by the system itself. The HC system will therefore decide when and how much energy to store, based on supply surplus and the energy being demanded by the loads. Some loads will be more sensitive than others, some will be intensive in power for a period of time, while others will consume energy on a moderate and regular basis. Therefore, at certain point some loads will occupy a higher hierarchy than others while some may be spared or serviced partially, as conditions change [3,4]. Such control mechanisms will involve both PH and RH operating in unison, determining a generalized state of energy equilibrium between supply and demand, as dynamic scenarios unfold [3,4].

Next we show the mathematical equations that represent the HC model incorporating homeostaticity capabilities by means of PH and RH. The expression representing the attainment of energy equilibrium in the SHES (grid-tied microgrid) installed in a residential or commercial building is given in terms of the total power supply by the metasystem (the microgrid plus the grid acting concomitantly), and the loads [3,4]. Homeostaticity in the energy system is achieved through homeostasis regulation mechanisms discussed previously, so that:

$E_{equilb} = P_{supply}(x)PH(u)RH(v)S(\alpha) = E_{consump}(u,v,\alpha) + \frac{d}{dt}E_{consump}(u,v,\alpha)$ and where $P_{supply} = Real\ Power + Reactive\ Power = (P+Q) - Losses$

Where x represents the internal state of the energy systems at time t = 0 and the Energy equilibrium Eq is dependent upon several factors operating in the SHES [14]. Both u and v represent the specific predictive and reactive homeostasis variables respectively, which are designed in the HC model. These are designed based on extensive data modeling to incorporate as much accuracy in the system's response as possible [4]. S(α) represents the conditioning function of the SHES and operates to alert and condition the system's adaptive capacity recursively in order to respond to a wide range of stimuli. Its actions are based on the situational awareness and degree of criticality being experienced by the metasystem (microgrid plus grid) and the solution incorporates AI algorithms and intelligent control. Thus S(α) is a function of the adverse conditions and environmental challenges being sensed by the energy system at any point and also foreseen in the near future. These are represented by the awareness and criticality variable α. Such variable may also be influenced by transient system conditions such as a sudden increase in reactive power demand in a reactive power constrained line, which is generally due to a contingency in transmission network causing an increase of the load burden of the adjacent line(s) in order to maintain the constant system loads, for example. All these three variables: u, v, α are the equivalent of metabolic variables in living organisms like the physiological and endocrine systems variables present in humans and animals which affect the system's energy expenditure and storage. The expression $\frac{d}{dt}E_{consump}(u,v,\alpha)$ stands for the rate of change of energy consumption of users, let us say a sustainable block [8-10,18-21] somewhere, and is a direct indicator of thriftiness and energy efficiency present in the metasystem. It is linked to powerful sustainability performance indicators of SES introduced previously in the literature [10], such as the homeostatic index H_i and the Grid_Frac [10]. The homeostatic index H_i is a powerful new concept previously introduced [10] which measures how much electricity is being consumed from the grid per home as a percentage of the total electricity (renewable plus non-renewable) being consumed by the entire sustainable block [9,10]. This is being monitored and recorded in real time and shown to the consumer as a monthly reading and/or on a daily and hourly basis, as preferred [9]. Thus homeostatic index H_i shows how thrifty and energy efficient each home is with respect to the power supplied by the microgrid [10]. This is important, not only because of what these two aspects of energy consumption represent but also because they drive the exergy level being built in the SHES.

Exergy is the maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment. Exergy also expresses the quality of a particular energy source and also quantifies the useful work done by a certain amount of energy employed [19,21,22] in any given process where there is energy intake and expenditure. Finally, we have that exergy is also defined as a measure of the actual potential of a system to do work with reference to a given environment. By means of the right homeostatic control (HC) strategies [9,10] and the given system conditions, one can elicit higher degrees of thriftiness and energy efficiency increasing the level exergy in the energy system. We should not forget that the energy system represents the microgrid tied to the grid both of which are connected to a number of energy consumers, all three acting concomitantly. A value of homeostatic index H_i below 1 is considered acceptable yet ideally values closer to 0.50 or below are a truer indicator of a high degree of thriftiness and energy efficiency for the home [10]. H_i is a measure of the energy efficiency and thriftiness of the energy consumers in a sustainable block.

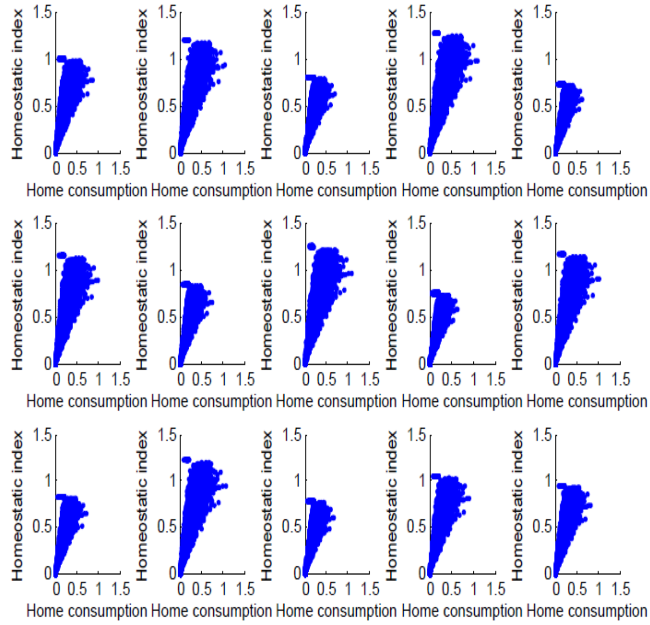

Fig.2 above is showing the simulation of H_i for 15 homes in a residential block supplied by a grid-tied micgrid [17].

On the other hand, Grid_Frac is an indicator of the fraction of total electricity drawn from the grid per each home. It is also a measure of EE and thriftiness just like the homeostatic index H_i whereas Grid_Frac shows the fraction (in percentage) of the total electricity consumption drawn from the grid by each home in the sustainable block [10]. Below is a diagram which illustrates the concepts presented here and incorporates an exergy index function which is also related to the quality of the energy being produced by the SHES and with the amount of thriftiness and EE being exercised by consumers which directly impacts $E_{consump}(u,v,\alpha) + \frac{d}{dt}E_{consump}(u,v,\alpha)$ determining how much energy is being made available in the energy system by the consumers of the sustainable block [10].

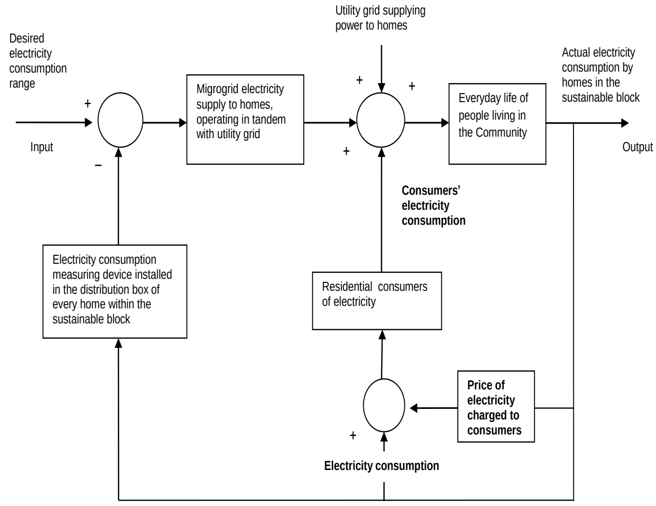

Fig.3. Flow diagram depicting the drivers of homeostatic control strategies to ensure efficient electricity supply and demand equilibrium based on energy and power consumption ranges per home consumers [10]. Source: owned elaboration.

In the model depicted above there is a particular control and energy management architecture involving independent energy sources and the grid. The sustainability of the system is in part safeguarded by AI algorithms that comprised the HC system which make up the autonomous mission control of the microgrid [9,10]. There is also an Exergy index function X_i that, like the homeostatic index, is a measure of the quality and efficiency of the energy being generated and utilized by the microgrid including the energy consumers in the sustainable block (the loads) [9,10]. The power supply by the SES is adjusted based on the block's homeostasis regulation (HR) and exergy indices for the whole sustainable block, based on aggregate demand of energy in the SHES [9,10].

However, in addition to the above, a good HC system operating within adequate performance levels of EE and thriftiness can greatly impact the exergy of the system and with this, effective and timely real and reactive power levels can be ensured to maintain system's stability through equilibrium between supply and demand. This can help keep short-term fluctuations in power requirements, both active and reactive power, from dropping the frequency or at least helping this situation become milder. This is because sometimes there are lags in the system's governor and generators' output which require a finite time to adjust to the new power requirements. Such actions can be aided by reactive and predictive homeostasis functions built into the system in order to act as an energy consumption-based frequency regulator,
$E_{consump}\,(u,v,\alpha) + \frac{d}{dt}E_{consump}(u,v,\alpha)$ aside from the role of power enabler. Such a role is played whenever EE and thriftiness in energy consumption make it possible for more power to be available in the system for those that need more while others need less [14,16,17]. No doubt the changing frequency in the SHES will influence the power flow but, at the same time, frequency is a function of the energy consumption and also the rate of change of such energy consumption, $E_{consump}\,(u,v,\alpha)$ therefore power flow and energy sustainability can also be influenced by $E_{consump}\,(u,v,\alpha) + \frac{d}{dt}E_{consump}(u,v,\alpha)$. The difference in energy consumption will impact system's frequency and voltage level, which will ultimately impact the power supply quality and overall system's dynamics in a sustainable hybrid energy system (SHES). We will talk about this further as we discuss next the reactive power role and how the prescribed energy and power management model can help reactive power management and thus voltage control.

With the droop method [60], however, the power angle depends heavily on the real power R generated while the voltage depends on the reactive power Q; AC systems like the grid supply or consume both: real power and reactive power, and when DG is operating tied to the grid, it can be difficult to maintain voltage levels. Real power accomplishes useful work on the loads that demand it while reactive power supports the voltage that must be controlled for system reliability and efficiency. In case of having DG systems tied to the grid like the utility-operated microgrid being discussed here, it is hard to control voltage, unlike when there is grid-only supply. This turns particularly true when sharp increases in power demand occur, as in early hours and towards the evening hours of the day. With homeostatic control of SHES it is easier to manager real and reactive power balance and to control reactive power in the grid-tied microgrid so as to ensure its effect on the reliability and security of EPS. This is so because HC enables reactive power management more easily by controlling the system's optimal equilibrium between supply and demand. Reactive power affects voltages throughout the system, and we all know how important and also difficult it is to keep voltage control steady in electrical power systems (EPS) in order for proper operation of electrical power equipment to prevent damage such as overheating of generators and motors, to reduce transmission losses and to maintain the ability of the EPS to withstand and prevent voltage sagging or simply power failure.
In general terms, when we decrease reactive power, we cause the voltage to fall while increasing it causes voltage to rise. A voltage sag or voltage collapse may occur when the system is being demanded beyond its capacity. This occurs when for example the grid-tied microgrid may try to supply too many loads at once, within a certain range of consumption, or it is being demanded too much power by certain loads at certain times, all of which plays against the homeostasis aquarium between supply and demand. This invariably will affect the voltage and the microgrid may not be able to support it. Regarding the latter and the importance of reactive power and how it is useful to maintain system voltage stability, homeostatic control of SHES seeks to do just that. If real power R can be adequately controlled, so can the power angle, and if the reactive power Q can be better regulated as well, then the voltage V will be controllable too [4,60]. The droop control method has an inherent trade-off between the active power sharing and the frequency accuracy, resulting in the frequency deviating slightly from the nominal frequency [4,60].

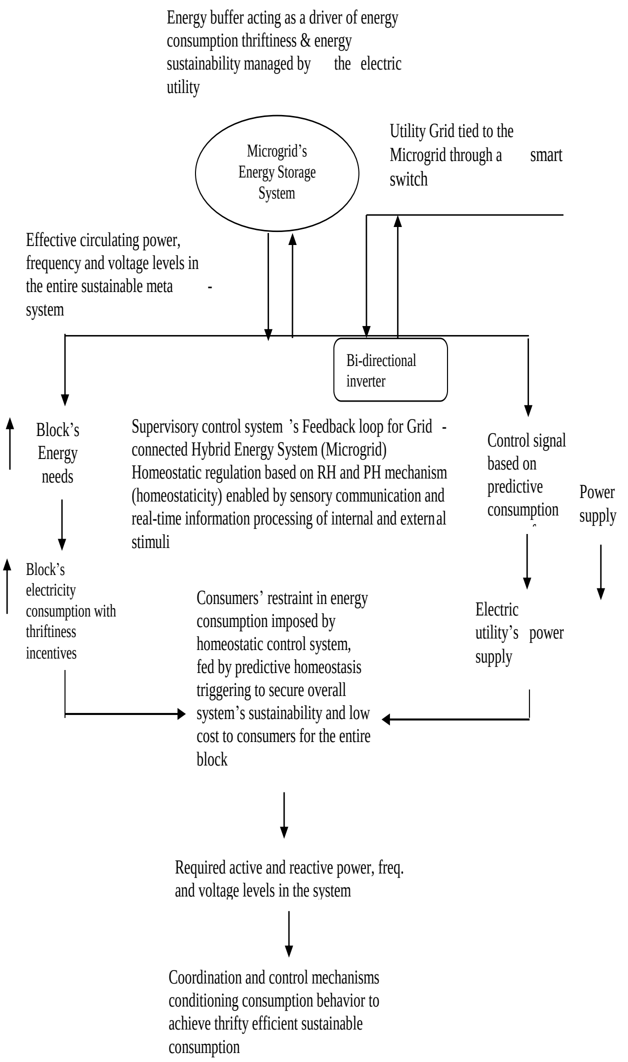

Fig.4. Energy homeostaticity mechanisms in operation for grid-connected microgrid operated by the utility with an energy buffer [10,4]. Source: own elaboration.

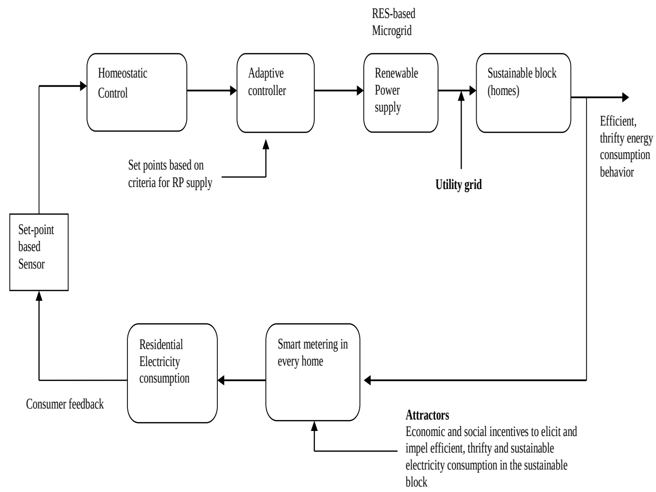

Fig.5 Predictive and reactive homeostasis mechanisms operate as part of the HC of the SHES, this time with energy storage [4,10]. Source: own elaboration.

3. Discussion

We extend the concept of homoeostatic control first introduced by Fred Schweppe and his team [61-64] back in the early 1980s, to include not only reactive homeostasis but also predictive homeostasis (PH), both of which can contribute to make SES more resilient, efficient and reliable while complementing more traditional control methods. PH involves a recursive set of mechanisms that triggers appropriate system responses in the prospect of near future stimuli manifestation [4]. In the case of sustainable energy systems, this constitutes a set of corrective responses initiated in anticipation of a predictably environmental (both internal and external) challenge. In general terms, predictive homeostasis is an anticipatory response to an expected homeostatic challenging event in the future. Seasonal migration of animals and birds in particular are examples of predictive homeostasis. Predictive responses often compromise the effectiveness of reactive homeostatic mechanisms, even to the point of risking the survival of the organism itself [4]. Nevertheless, both predictive and reactive homeostasis (RH) must be in equilibrium and perfectly synchronized just as large rotating AC generators must operate in synchrony with the frequency of the grid. If this was not the case and both RH and PH were to operate uncoordinatedly, they may become in conflict with each other. In such cases predictive responses may compromise the effectiveness of reactive homeostatic control mechanisms to the point of jeopardizing the sustainability of the energy system [4]. There are many examples of such catastrophes in recent history and everything seems to indicate that things aren't getting any better and that more severe weather patterns are expected along with natural disasters. Chile, in particular, bears a good example of such calamities, showing just how much chaos and destruction they can bring to the population. The February 27th, 2010's giant earthquake and tsunami are still vivid in the memory of Chileans and there is clear memory of how the major electric power and telecommunications networks collapsed as a result. There have also been more frequent occurrences of strong winds, and large fires extending to forest and urban areas, and volcano eruptions, all of which cause havoc in our energy and communication networks [4].

4. Conclusions

Climate change and natural disasters are a very serious threat that has brought worldwide attention and demands concrete actions now. World leaders have understood this and have been meeting to discuss this issue and to explore mitigation measures for several years. Nature doesn't give man a second chance, either you are prepared or you aren't. It is therefore imperative that we understand that traditional electric power infrastructure is not only vulnerable but also dangerous and ineffective when it comes to natural disasters or harsh climate like strong winds, earthquakes and floods, all of which are part of an ever more complex environmental scenario. These and other dangerous phenomena like sinkholes and rising sea tides are also affecting modern infrastructure and mankind's way of life just about everywhere. Thus decentralizing power systems by means of DG solutions employing both renewables and traditional power sources like a SES makes sense. The concept of energy hubs is also part of this new power infrastructure vision with a much more sensible and reliable architecture than traditional energy matrix that relies on long transmission and distribution lines. Furthermore, if we can equip these systems with adequate communications capabilities and data sensing devices operating in interconnected fashion, in all systems comprising the power generation and distribution chain, this would make a better solution. It can be done using simple microprocessor-based technology with set-points data signals programmed in the microprocessor itself for the control of the entire system in a hybrid, distributed fashion, where there is a central controller interacting with each sub-system's controller as well as with the electric utility control operator as well. That would allow for a more flexible, inexpensive, fast and robust control system than the more expensive, complex systems such as multi-agent systems or expert systems that much of the current literature on smart grid and intelligent computing is embracing. At least for smart microgrids to supply electricity and potentially heat using CHP as a generation alternative for the distribution grid [33,65-68] for cases in which a natural disaster strikes, leaving a whole neighborhood without power, a simpler, more flexible, economical and modular control solution is possible [8,10]. This paper offers a glimpse of such new solutions, as there are others which point to the same necessity in the current Smart Grid era of giant-leap type transformations in the electric utilities' industry sector [69-71] incorporating reactive and predictive homeostasis control mechanisms, which are part of the new frontier of control and communications systems engineering.

Electricity infrastructure is feeble and largely outdated when it comes to the electric power distribution sector in Chile, as it hasn´t kept up with the times. Environmental challenges like natural disasters and severe weather patterns brought by phenomena like El Niño leave no room for preambles. In spite of electricity being the blood flow that powers all sectors of the country, little if anything has been done to counteract environmental and other threats (like terrorist acts, for example) that put power supply stability at risk. Nevertheless, at the present time, there are electric utilities in the world exploring new solutions to a grave and growing problem. Enel Distribucion in Chile is one of them. This paper presents a new control model to incorporate SHES in residential, commercial and other institutions like schools, hospitals and airports, to serve as a localized energy solution that can complement the power grid. Its engineering design and homeostatic control capabilities incorporate reactive and predictive homeostasis which allow for homeostaticity to occur in energy systems. We also believe this crusade should be led by electric utilities like ENEL with the aid of appropriate legislation by the government. This new model may very well coexist and complement more traditional control and energy management methods like droop control to better equip the system with better environmental challenge management and resilience capacity.

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References

[1] Cannon, W. B. (1929). Organization for physiological homeostasis. *Physiological reviews*, *9*(3), 399-431.

[2] Cannon, W. B. (1935). Stress and strains of homeostasis. *American Journal of Medical Science*, *189*, 1-14.

[3] Yanine, F., Sanchez-Squella, A., Barrueto, A., Cordova, F., & Sahoo, S. K. (2017). Engineering Sustainable Energy Systems: How Reactive and Predictive Homeostatic Control Can Prepare Electric Power Systems for Environmental Challenges. *Procedia Computer Science*, *122*, 439-446.

[4] Yanine, F., Sanchez-Squella, A., Barrueto, A., Tosso, J., Cordova, F. M., & Rother, H. C. (2017). Reviewing homeostasis of sustainable energy systems: How reactive and predictive homeostasis can enable electric utilities to operate distributed generation as part of their power supply services. *Renewable and Sustainable Energy Reviews*.

[5] https://www.congress.gov/bill/114th-congress/senate-bill/2012 Retrieved Feb 2, 2018.

[6] https://microgridknowledge.com/think-microgrid-government-leaders-serious-quest-build-microgrids/ Retrieved Feb 2, 2018.

[7] https://www.cleanegroup.org/ceg-resources/resource/resilient-power-evolution-of-a-new-clean-energy-strategy-to-meet-severe-weather-threats. Retrieved Feb 2, 2018.

[8] Cordova, F. M., & Yanine, F. F. (2013). Homeostatic control of sustainable energy grid applied to natural disasters. *International Journal of Computers Communications & Control*, *8*(1), 50-60.

[9] Yanine, F. F., Caballero, F. I., Sauma, E. E., & Córdova, F. M. (2014). Homeostatic control, smart metering and efficient energy supply and consumption criteria: A means to building more sustainable hybrid micro-generation systems. *Renewable and Sustainable Energy Reviews*, *38*, 235-258.

[10] Yanine, F. F., Caballero, F. I., Sauma, E. E., & Córdova, F. M. (2014). Building sustainable energy systems: Homeostatic control of grid-connected microgrids, as a means to reconcile power supply and energy demand response management. *Renewable and Sustainable Energy Reviews*, *40*, 1168-1191.

[11] https://earthsky.org/earth/powerful-earthquake-strikes-off-chiles-coast Retrieved Feb 2, 2018.

[12] http://www.britannica.com/event/Chile-earthquake-of-2010 Retrieved Feb 2, 2018.

[13] https://microgridknowledge.com/hybrid-microgrids/ Retrieved Feb 2, 2018.

[14] http://www.iea.org/Textbase/npsum/US2014sum.pdf Retrieved Feb 2, 2018.

[15] https://energypedia.info/wiki/Net-Metering_/_Billing_in_Chile Retrieved Feb 2, 2018.

[16] https://www.enel.com/media/press/d/2016/06/enel-presents-enel-open-meter-the-new-electronic-meter Retrieved Feb 2, 2018.

[17] https://www.eneldistribucion.cl/medicion-inteligente Retrieved Feb 2, 2018.

[18] Yanine, F. F., & Sauma, E. E. (2013). Review of grid-tie micro-generation systems without energy storage: Towards a new approach to sustainable hybrid energy systems linked to energy efficiency. *Renewable and Sustainable Energy Reviews*, *26*, 60-95.

[19] Yanine, F. F., Sauma, E. E., & Cordova, F. M. (2014). An exergy and homeostatic control approach to sustainable grid-connected microgrids without energy storage. In *Applied Mechanics and Materials* (Vol. 472, pp. 1027-1031). Trans Tech Publications.

[20] Caballero, F., Sauma, E., & Yanine, F. (2013). Business optimal design of a grid-connected hybrid PV (photovoltaic)-wind energy system without energy storage for an Easter Island's block. *Energy*, *61*, 248-261.

[21] Yanine, F. F., Córdova, F. M., & Valenzuela, L. (2015). Sustainable hybrid energy systems: an energy and exergy management approach with homeostatic control of microgrids. *Procedia Computer Science*, *55*, 642-649.

[22] Yanine, F., & Córdova, F. M. (2013, March). Homeostatic control in grid-connected micro-generation power systems: A means to adapt to changing scenarios while preserving energy sustainability. In *Renewable and Sustainable Energy Conference (IRSEC), 2013 International* (pp. 525-530). IEEE.

[23] https://obamawhitehouse.archives.gov/sites/default/files/image/president27sclimateactionplan.pdf Retrieved Feb 2, 2018.

[24] Blake, E.S., Kimberlain, T.B., Berg, R.J., Cangialosi, J.P., Beven, I.I. and John, L., (2013). National Hurricane Center (February 12, 2013).

Hurricane Sandy: October, 22, p.29. (PDF) (Tropical Cyclone Report). United States National Oceanic and Atmospheric Administration's National Weather Service. Archived from the original on February 17, 2013. Retrieved February 1, 2018

[25] Diakakis, M., Deligiannakis, G., Katsetsiadou, K. and Lekkas, E., (2015). Hurricane Sandy mortality in the Caribbean and continental North America. Disaster Prevention and Management, 24(1), pp.132-148.

[26] Hurricane/Post-Tropical Cyclone Sandy, October 22–29, 2012 (PDF) (Service Assessment). United States National Oceanic and Atmospheric Administration's National Weather Service. May 2013, p. 10. Archived from the original on June 2, 2013. Retrieved Feb 2, 2018.

[27] http://www.livescience.com/22522-hurricane-katrina-facts.html Retrieved Feb 2, 2018.

[28] Che, L., Khodayar, M., & Shahidehpour, M. (2014). Only connect: Microgrids for distribution system restoration. *IEEE Power and Energy Magazine*, *12*(1), 70-81.

[29] Che, L., & Shahidehpour, M. (2014). DC microgrids: Economic operation and enhancement of resilience by hierarchical control. *IEEE Transactions on Smart Grid*, *5*(5), 2517-2526.

[30] Wang, Z., & Wang, J. (2015). Self-healing resilient distribution systems based on sectionalization into microgrids. *IEEE Transactions on Power Systems*, *30*(6), 3139-3149.

[31] Chen, C., Wang, J., Qiu, F., & Zhao, D. (2016). Resilient distribution system by microgrids formation after natural disasters. *IEEE Transactions on smart grid*, *7*(2), 958-966.

[32] Roach, M., & Horizons, M. (2012). Hurricane Sandy & the Emperor's New Clothes: Microgrids as a Risk Mitigation Strategy for Extreme Weather Events. *White Paper, MicroGrid Horizons*.

[33] Hedman, B. (2007). Combined Heat and Power and Heat Recovery as Energy Efficiency Options. *Presentation on behalf of US CHP Association and ICF Consulting, Washington, DC*.

[34] Olinsky-Paul, T. (2013). Using State RPSs to Promote Resilient Power at Critical Infrastructure Facilities. *Clean Energy States Alliance, May*.

[35] Steg, L., Perlaviciute, G., & van der Werff, E. (2015). Understanding the human dimensions of a sustainable energy transition. *Frontiers in psychology*, *6*, 805.

[36] http://www.cleanegroup.org/assets/2015/Resilient-States.pdf

[37] Dixon, R. K., McGowan, E., Onysko, G., & Scheer, R. M. (2010). US energy conservation and efficiency policies: Challenges and opportunities. *Energy Policy*, *38*(11), 6398-6408.

[38] Rogers, R. P. (2003). The effect of the Energy Policy and Conservation Act (EPCA) regulation on petroleum product prices, 1976-1981. *The Energy Journal*, 63-93.

[39] Grantham, S. Power to the People: CL&P's Crisis Communication Response Following the 2011 October Nor'easter.

[40] https://www.cleanegroup.org/ceg-resources/resource/resilient-power-evolution-of-a-new-clean-energy-strategy-to-meet-severe-weather-threats/

[41] Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research*, *127*, 259-270.

[42] Campbell, R. J. (2012, August). Weather-related power outages and electric system resiliency. Washington, DC: Congressional Research Service, Library of Congress.

[43] https://edition.cnn.com/2015/09/16/americas/chile-earthquake/index.html Retrieved Feb 2, 2018.

[44] Olivares, D. E., Mehrizi-Sani, A., Etemadi, A. H., Cañizares, C. A., Iravani, R., Kazerani, M., ... & Jimenez-Estevez, G. A. (2014). Trends in microgrid control. *IEEE Transactions on smart grid*, *5*(4), 1905-1919.

[45] Jones, K. B., Bartell, S. J., Nugent, D., Hart, J., & Shrestha, A. (2013). The urban microgrid: Smart legal and regulatory policies to support electric grid resiliency and climate mitigation. *Fordham Urb. LJ*, *41*, 1695.

[46] Khodaei, A. (2014). Resiliency-oriented microgrid optimal scheduling. *IEEE Transactions on Smart Grid*, *5*(4), 1584-1591.

[47] Warshay, B. (2015). Upgrading the Grid: How to Modernize America's Electrical Infrastructure. *Foreign Aff.*, *94*, 125.

[48] Sallam, A. A., & Malik, O. P. (2011). *Electric distribution systems* (Vol. 68). John Wiley & Sons.

[49] Walker, G., Hunter, S., Devine-Wright, P., Evans, B., & Fay, H. (2007). Harnessing community energies: explaining and evaluating community-based localism in renewable energy policy in the UK. *Global Environmental Politics*, *7*(2), 64-82.

[50] Ding, J. J., & Buckeridge, J. S. (2000). Design considerations for a sustainable hybrid energy system. *Transactions of the Institution of Professional Engineers New Zealand: Civil Engineering Section*, *27*(1), 1.

[51] El-Khattam, W., & Salama, M. M. (2004). Distributed generation technologies, definitions and benefits. *Electric power systems research*, *71*(2), 119-128.

[52] Walker, G. What are the barriers and incentives for community-owned means of energy production and use? (2008), Energy Policy 36, no. 12: 4401-4405.

[53] Wearing, S. L., Wearing, M., & McDonald, M. (2010). Understanding local power and interactional processes in sustainable tourism: Exploring village–tour operator relations on the Kokoda Track, Papua New Guinea. *Journal of Sustainable Tourism*, *18*(1), 61-76.

[54] Geidl, M., Koeppel, G., Favre-Perrod, P., Klockl, B., Andersson, G., & Frohlich, K. (2007). Energy hubs for the future. *IEEE power and energy magazine*, *5*(1), 24-30.

[55] Huang, A. Q., Crow, M. L., Heydt, G. T., Zheng, J. P., & Dale, S. J. (2011). The future renewable electric energy delivery and management (FREEDM) system: the energy internet. *Proceedings of the IEEE*, *99*(1), 133-148.

[56] Bozchalui, M. C., Hashmi, S. A., Hassen, H., Cañizares, C. A., & Bhattacharya, K. (2012). Optimal operation of residential energy hubs in smart grids. *IEEE Transactions on Smart Grid*, *3*(4), 1755-1766.

[57] Fettweis, G., & Zimmermann, E. (2008, September). ICT energy consumption-trends and challenges. In *Proceedings of the 11th international symposium on wireless personal multimedia communications* (Vol. 2, No. 4, p. 6). (Lapland.

[58] Zinaman, O., Miller, M., Adil, A., Arent, D., Cochran, J., Vora, R., ... & Kauffman, R. (2015). *Power systems of the future: a 21st century power partnership thought leadership report* (No. NREL/TP-6A20-62611). NREL (National Renewable Energy Laboratory (NREL), Golden, CO (United States)).

[59] Hartmanns, A., & Hermanns, H. (2012, October). Modelling and decentralised runtime control of self-stabilising power micro grids. In *International Symposium On Leveraging Applications of Formal Methods, Verification and Validation* (pp. 420-439). Springer, Berlin, Heidelberg.

[60] Bollman, A. M. (2010). An experimental study of frequency droop control in a low-inertia microgrid.

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

[62] Schweppe, F. C., Tabors, R. D., & Kirtley, J. L. (1981). Homeostatic control: the utility customer marketplace for electric power.

[63] Schweppe, F. C., Tabors, R. D., & Kirtley, J. L. (1982). Power/energy: Homeostatic control for electric power usage: A new scheme for putting the customer in the control loop would exploit microprocessors to deliver energy more efficiently. *IEEE spectrum*, *19*(7), 44-48.

[64] Amin, M. (2003). North America's electricity infrastructure: Are we ready for more perfect storms? *IEEE Security & Privacy*, *99*(5), 19-25.

[65] Amin, M. (2001). Toward self-healing energy infrastructure systems. *IEEE Computer Applications in Power*, *14*(1), 20-28.

[66] Amin, S. M., & Wollenberg, B. F. (2005). Toward a smart grid: power delivery for the 21st century. *IEEE power and energy magazine*, *3*(5), 34-41.

[67] Amin, M., & Schewe, P. F. (2007). Preventing blackouts. *Scientific American*, *296*(5), 60-67.

[68] Afzal, A., Mohibullah, M., & Kumar Sharma, V. (2010). Optimal hybrid renewable energy systems for energy security: a comparative study. *International Journal of Sustainable Energy*, *29*(1), 48-58.

[69] Tricoire, A. (2015). Uncertainty, vision, and the vitality of the emerging smart grid. *Energy Research & Social Science*, *9*, 21-34.

[70] Rearte-Jorquera, A., Sánchez-Squella, A., Pulgar-Painemal, H., & Barrueto-Guzmán, A. (2015). Impact of Residential Photovoltaic Generation in Smart Grid Operation: Real Example. *Procedia Computer Science*, *55*, 1390-1399.

[71] Uckun, C. (2012). *Dynamic electricity pricing for smart homes*. The University of Chicago.