



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



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ABSTRACT

Homeostatic control (HC) of electric power systems (EPS), particularly those that fall into the distributed generation (DG) category, can enable utilities to broaden their power supply services in line with industry changes worldwide while at the same time safeguarding their customers' power supply against environmental challenges. Such solutions are being considered nowadays by industry giants like ENEL, by far the largest electric power utility operating in Chile. ENEL is seeking to tap into the DG market with a microgrid solution that can be installed in every building that is part of its customer base. In order to accomplish this, such DG solutions should first and foremost behave like sustainable energy systems (SES). For this they ought to emulate homeostasis mechanisms present in all living organisms. Both reactive homeostasis (RH) and predictive homeostasis (PH) enable living organisms to respond early and proactively to internal changes in the grid-tied DG system as well as to environmental challenges and threats. Particularly PH does so by foreseeing when these are most likely to occur, adjusting their energy intake and expenditure accordingly to maintain a stable, efficient and sustainable equilibrium. Based on the above, this paper presents a theoretical approach with an empirical base for engineering sustainability in hybrid energy systems. The project is part of a joint research initiative between a small group of university researchers and ENEL Distribucion, formerly Chilectra¹ of Chile to develop a commercial prototype to be implemented in apartment buildings being serviced by ENEL throughout Santiago. This is important in order to advance DG solutions implemented by utilities like ENEL Distribucion, to further EPS decentralization, offer a broad, more flexible and personalized spectrum of services and, at the same time, preparing them for growing environmental challenges and threats.

1. Introduction

Ever since Cannon [1,2] first introduced the concept, attention on homeostasis has been focused chiefly on its role in medicine and biology to find cures for diseases like diabetes and obesity for example. However, homeostasis applications in designing and engineering sustainable energy systems (SES) are also part of its focus and scientific work scope, realizing that exergy and sustainability are both directly linked to homeostasis mechanisms present in all living systems. This is so because exergy is part of such mechanisms and expresses the capacity of the system to do useful work at any time, and to bring the system into efficient equilibrium. This

systemic capacity is enhanced whenever energy efficiency (EE) and thriftiness are combined with reactive and predictive homeostasis, as it is presented in a generic homeostatic control (HC) system proposed in this paper, along with the theoretical and empirical foundations that sustain it. The HC system proposed here is the result of an ongoing joint research and development effort between ENEL Distribucion and the corresponding author's industry research team. The HC system is to be built beginning in 2017 to operate ENEL's utility-run microgrid project to be implemented in a number of buildings, whereby customers and the utility are expected to contribute to potentiating each other's role in this new energy scenario.

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¹ ENEL Distribucion is one of the main electric power distribution companies in Chile and is part of the ENEL Group.

In today's electric utilities market two main concerns arise. First there is the need to advance towards further electric power systems (EPS) decentralization, incorporating more renewables and furthering the opportunity to incorporate distributed generation (DG) along with smart grid technologies to the energy grid, and to offer more flexible, personalized and cost effective services. This is going on in tandem with the industry transformation that is taking place worldwide towards the adoption of Smart Grid technologies, as is the case in Chile where new legislation is emerging to force the industry to open up and become much more competitive than in the past.

The second big concern in Chile is the increasing threat coming from climate change and the ever more frequent problem of quakes and fires, something which greatly affects the traditional EPS infrastructure [3–6]. Environmental challenges like natural disasters and hazardous climatic events are becoming more severe and recurrent in many parts of the world including Chile, and they are here to stay, affecting millions.

Nowhere is the matter being taken more seriously than in the United States, where the U.S. Senate was expected to take up microgrid policy in early 2016 to tackle, among others, the issue of electric power grid readiness and resilience [7–9]. In North America, for example, large-scale power outages spanning several urban and semi-rural areas are not new. Still fresh in people's memory is Hurricane Sandy, known as 'Superstorm Sandy' [10–13]. 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 [10–13] with damages estimated as of 2015 to have been about \$75 billion (2012 USD), a total surpassed only by Hurricane Katrina [14,15]. 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, the Hurricanes Katrina and Rita in 2005 and Hurricane Irene and the Northeast's freak Halloween snowstorm in 2011 [14]. After each of these events, more consensuses were built among public opinion, local authorities and power industry experts that something new had to be done fast to strengthen the power distribution grid against such recurrent catastrophes.

Even in the best case scenarios, where everything seems to go smooth, the electricity grid may experience short-term, temporary changes in overall capacity that may adversely impact power supply and cause severe problems. Thus electric utilities must be prepared to face such disruptions and to account for power plant malfunctions or transmission lines that suddenly go out of service, resulting in a power outage [16,17]. Also rapid and unexpected increases or decreases in electricity demand can cause abrupt and unforeseen changes in frequency and voltage, affecting hundreds of thousands of customers. Particularly electric utilities in Chile are becoming increasingly concerned about such threats and the power disruptions the poise. Even small voltage variations that were common in the past are now unacceptable, since changes in the law now obligate electric power suppliers to indemnify their customers for any damage to their customers' goods. Appliances, PCs, and a variety of infrastructure damage, can be at risk. They are also accountable for damages and can be forced to respond for financial losses to any residential or commercial customer that may be affected by a power malfunction or unplanned power outage. Therefore the need to become much more resilient, robust and, at the same time, more flexible, has made them refocus their priorities, and embrace more localized, smaller EPS employing renewables.

Electric utilities like ENEL are also seeking to increase their ability to attenuate or ameliorate peak demand hurdles, smoothing out peaks and troughs in their energy supply and looking for ways to incentivize a more balanced and efficient energy consumption, in order to respond more effectively and proactively to changing energy needs and to environmental disruptions. In this respect, ENEL Distribucion in Chile has pioneered the smart metering service for its customers by

implementing its "**Sistema de Medicion Inteligente**" (<https://www.eneldistribucion.cl/medicion-inteligente>). Intelligent Measurement is a solution made up of new, smart measurement equipment, telecommunications infrastructure and central systems that allow remote and automated management of the meters through a bidirectional flow of information through the electrical networks, optimizing the operation of the meters, contributing to improve the Reliability, safety and quality of the electric service. In the case of renewables as a sustainability factor in the pool of energy supply options, Chile, with abundant wind in the northern part of the country and having one of the best solar irradiations in the world, is a big player; plus there has been better legislation enacted in recent times to make the energy grid more competitive, which has brought important changes to the country's EPS industry scenario. More wind, solar and other renewables are expected to be incorporated to the power grid in the coming years, and their contribution will further reinforce power supply providing more alternatives to local communities. This will also give more power to the regions in Chile, where these resources are being exploited, in opposition to the past when the central government monopolized all the decisions and decided purely on a centralized and highly hierarchized political criterion with little or no regard for regional interests.

With storage technologies maturing such as lithium batteries (lithium is quite abundant in Chile and there are plans to exploit this technology in the coming years) or hydrogen production, not only for electricity but also for all electric public transportation; it is evident that their integration with the current EPS infrastructure is a matter of time. Yet this would only be possible with a smart grid transformation. ENEL knows this and is keenly aware of the need for such industry changes in a country, with several conditions which favor these changes; and is aggressively moving in that direction. ENEL and other utilities are also considering high power DC grids to face mounting costs of building new AC transmission lines which generate tremendous costs and bring chaos and disruption to local communities, especially to agricultural and farming regions.

In Chile in particular, being such a long country, rich in natural and renewable energy resources, and with huge hurdles to advance transmission lines, there is the need to explore more flexible, small and medium-range scale DC solutions, as well as other medium range power supply alternatives that can operate as energy hubs. Particularly in the far south and north of Chile, where there are growing plans to integrate electric power services with neighboring countries like Argentina and to provide electricity to vast zones in those countries, such as Peru and vast regions of Argentina, it is all too clear for utilities like ENEL that the future of electric power generation, distribution and consumption will rely chiefly on regional integration, and their ability to deliver it efficiently, safely and sustainably.

The paper is divided into five sections. **Section 1** serves as the introduction, emphasizing the need for SES in light of ongoing changes in the electric power systems (EPS) industry in Chile and the threats that climate change and particularly the current EPS' infrastructure-related energy crisis poise. The section also underlines the hurdles of the EPS decentralization and the roadblocks for adopting and engineering SES, and particularly sustainable hybrid energy systems (SHES) such as the microgrid concept. **Section 2** presents a brief review of the HC systems literature and then points to the need to incorporate homeostasis-based control systems in the design of SES, particularly in line with the opportunity at hand, where electric power industry icons like ENEL are considering to present to the market for the incorporation of such systems. **Section 3** presents a homeostasis-based power and energy management system for a sustainable hybrid energy system (SHES) like the microgrid. The new homeostasis-based power and energy management and control system being proposed here compares more traditional control methodology with the new theoretical approach being presented. **Section 4** deals with SHES and the need to view and manage sustainable hybrid energy systems

(SHES) as living open systems. This section offers a discussion section as well to enhance our insight and to enlighten the subject's industry spectrum and emerging focus on a more localized, flexible and less vulnerable to disruption of power supply due to harsh climate conditions and other unforeseen factors, than what we have at the present time, in light of its modern day transformation, where Chile is no stranger. Section 5 offers conclusions.

1.1. Climate change and the energy crisis: building the case for sustainable energy systems (SES) in the electric utilities' landscape

Like the US, Chile is no stranger to these harsh scenarios either, and has had its share of disasters too. The country is 'sitting on a hot seat' so to speak, with earthquakes, volcano eruptions, strong winds 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 events 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 water supply, roads, electric power transmission and distribution networks, and telecommunications are a vital part, yet increasingly vulnerable when faced with these phenomena [3,16,17].

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 [4,5]. 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 [6] was much worse and found the country largely unprepared. It occurred on February 27, 2010 at 3:34 a.m., 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 [6]. Yet, despite the powerful and devastating experience of these and other natural disasters, the country remains largely unprepared against massive telecomm and electric power systems brake-down [3].

The problem lies unfortunately in the high concentration of centralized electric power and communication systems—a model not easy to change, that once proved efficient and secure but that it is no longer. To further compound the risks posed by environmental threats, there is also the lack of adequate technologies and back-up/ emergency power systems for disaster recovery, something that even extends to the armed forces of the country today. There is really no energy sustainability roadmap for the country whatsoever, aside from a timid effort to advance in the incorporation of non-conventional renewable energies. Environmental policy is also weak and short sighted, owing to strong corporate interests and lobby to keep the status quo in order to continue superseding environmental management to corporate economic interests.

The flaws that are built into the very fabric of our presently centralized power systems were on full display in the aftermath of the Feb. 27th, 2010 earthquake in Chile [6]. Nowhere it becomes 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. Thus, the large power and telecommunication networks that once proved very efficient, stable and secure, are now at the center of discussion fueling the need for decentralization, further upgrades in technology for the national energy grid matrix and the rapid growth of distributed generation (DG). Hence it makes sense to follow other nations' example seeking more decentralized, diversified and DG-

oriented energy matrix, a solution that is notoriously much better suited to withstand such disasters [7–28].

1.2. The hurdles of electric power systems (EPS) decentralization and the roadblocks for adopting and engineering SES

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 blaming the link of the actual chain. Due to its geography and utility infrastructure design and operational conditions, Chile is a country that is quite vulnerable and susceptible to be struck by natural disasters including landslides, floods and earthquakes which can seriously impair its utility infrastructure let alone roads and transportation. Such events can cause major damage, producing havoc and mayhem all around, compromising the operation of key infrastructure like the power grid, water and sewage. 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 [7–10,17,18].

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. For this very reason, DG solutions ought to be designed around the idea of flexibility, resourcefulness and independence brought by semi-autonomous systems like the grid-tied microgrid, 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. 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. 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.

Although of great concern for millions of people, particularly for those countries where the technology is currently being used, the nuclear energy issue is still a double edged knife, with disastrous implications to humanity should an accident or negligent act were to 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 quite 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 so we'll leave it out. 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. Although economically efficient, traditional centralized EPS (including nuclear energy) are not only vulnerable in regards to natural disasters and other environmental challenges including vandalism and sabotage, which may threaten our energy supply, presenting very little flexibility and no diversification of energy sources. There is also the fact that EPS' infrastructure vulnerability and its collateral damage manifest themselves in various 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, causing huge public outcry like the failed Hidroaysen project (<http://www.futurorenovable.cl/hidroaysen-es-un-proyecto-fallido/>) in southern Chile, plus economic and social havoc with grave disruptions to the life of local communities.

Centralized electric power generation and distribution systems as

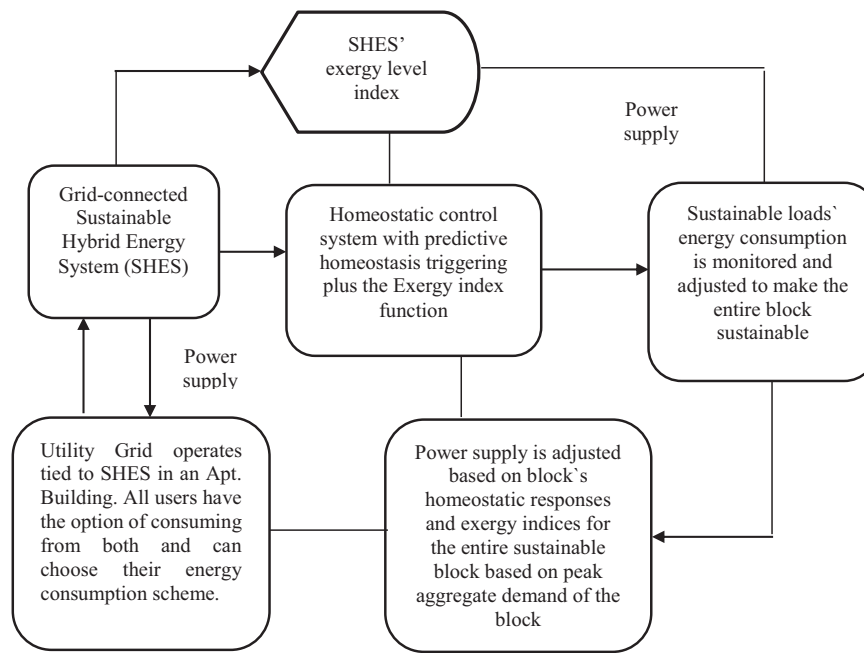


Fig. 1. The diagram depicts reactive and predictive homeostasis mechanisms engineered in the HC of the SHES (microgrid) to be installed in an apartment building in Santiago, Chile. Source: Own elaboration.

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 are never more evident and alarming than 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 [4–6]. 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 [27,28]. 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 power disruption dramatically (because of existing generation and distribution power topologies) [27,28].

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. 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 [3,31–37]. Hopefully, adequate legislation initiatives will be more forthcoming in the years to come, bringing changes that can make the transition to a more secure, robust, resilient and better prepared EPS come to fruition.

1.3. The shift in microgrid trends from a more passive role to a more active industry player

While this is no longer the case, DG solutions like the microgrid or diesel generator sets were first thought for remote and isolated areas only, and designed as back-up systems in case of a power outage or else because grid power was unreliable or simply non-existent, like in many parts of Canada where no transmission lines exist. Yet in many places in Latin America and elsewhere in the world there are still 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, just like the North American trend shows [18–28,40–46].

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. In order to operate autonomously or semi-autonomously so as to reliably supply electricity and heat to a local community, whether it be 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 [29–39]. 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 or equipment malfunction, 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 recently passed in Chile [47] 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 commu-

nities, power utilities and independent local operators are likely to emerge [23–39], 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 [48–52].

As can be seen on Fig. 1 the diagram illustrates how HC mechanisms, based on reactive and predictive homeostasis, trigger a system's sustainability stress response that imposes a restraint over energy consumption of loads, based on the energy supply being available in the system.

In the above diagram there is no energy storage and the Grid operates as back-up. Both homeostatic control (HC) and artificial intelligence (AI) can play a substantive role in developing SES' capabilities, understanding that homeostasis encompasses both reactive and predictive responses of such systems to changes in internal system's variables as well as changes in the environment.

The interesting Smart Grid concept of energy hubs [40,41] built around the current EPS infrastructure is an idea worth exploring for Chile, where such localized energy hubs could be built incrementally provided adequate legislation and industry incentives in order to transition to a new EPS reality braking away with the old unfit paradigm of today's power long distance transmission and distribution network. SES 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 now are seeing 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 sharp fall in certain energy generation technologies like solar and some wind turbines, along with a plague of very bad weather and natural disasters like torrential rains, earthquakes and landslides have accelerated this change from a more traditional mind frame to a modern, more proactive and customer-conscious and responsive approach on the part of industry agents, local authorities and legislators.

2. The need to incorporate homeostasis-based control systems in the design of sustainable energy systems

Ever 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 [31–42]. Sustainable energy systems encompass both reactive and predictive homeostasis operating recursively and in coordination with one another in the face of an environmental challenge.

On the other hand, homeostatic control is a term first introduced by F. C. Schwegge and his group of collaborators at MIT back in 1979 and in early 1980s [53–60] which stems from their highly visionary work and insight regarding both, flexibility and stability in electric power systems (EPS) linked to homeostasis, understood as reaching and maintaining an efficient equilibrium state between energy supply and demand, considering the diverse nature and operation dynamics of the wide variety of industrial and commercial loads [53–60]. Their approach advocated homeostatic control (HC) of energy supply and

demand in an effort to make utilities power supply more efficient, particularly when supplying large industrial and commercial customers. Indeed Schwegge and his group were much ahead of their time, having had a true insight for what was to come in the years ahead, anticipating also the need for new control technologies and energy management systems to adequately manage the intermittent supply of RETs (mostly wind back then). Homeostasis mechanisms applied to EPS allow utilities to finding ways to tap into a number of opportunities that the great variety of energy consumption patterns of their customers, therefore enabling them to better manage their supply capacity, and at the same time, finding new ways to best fit renewable energy sources and technologies into the current electric power infrastructure [31–37,61–63]. Something in which there are still much to be done, especially in a country like Chile.

2.1. Reactive and predictive homeostasis to control sustainable energy systems

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. This can be engineered in SES by employing sensors, control limit actuators (for example set-point fired responses) and (artificial intelligence) AI algorithms that allow the system to make decisions to respond to changes in a predetermined array of systems control variables. Thus SES take actions to counteract or fend off adverse conditions and noise that may affect the system's normal operation.

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 sustainable energy system to immediately prepare itself, taking the necessary precautions and actions to adapt and even reconfiguring 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 resourcefulness in terms of its readiness control mechanisms. 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 at a longer time in advance of a probable environmental challenge. However, as we all know, dynamic open systems like the microgrid's supervisory control system are prone to internal conflicts when control criteria superimpose on one another generating the wrong response.

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. 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 sequence which, if inadequately engineered in the SES, may result in inadvertent antagonism that can hurt system's performance [31–34,36,37]. 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 [31–37,61–63].

Thus adequate measures must be engineered in the system's design to prevent PH responses from 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.

3. The Homeostasis-based power and energy management system for SES like the microgrid

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 an ample array of control mechanisms ready to act whenever conditions arise. Therefore energy homeostasis in SES requires a careful equilibrium of such control mechanisms and the coordination of internal and external decision variables—all part of the particular HC strategy designed in the SES—which will stand guard against a variety of adverse conditions and possible challenges. Thus the SES 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 SES capable of supplying. The question of if and how much energy will go into the energy storage system 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 demanded by the loads. Some loads will be more sensitive than others and therefore will occupy a higher hierarchy while others may be spared or serviced partially, as conditions change. Such HC 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 [30–37,61–65].

3.1. Building sustainability in energy systems: the role of thriftiness and energy efficiency in the drive for higher systems efficiency and exergy levels

Proposition 3.1.1.: Energy homeostasis is present in all living organisms. As such it is also present in living sustainable energy systems [1,2,31,33,35,53–60].

Corollary.: Energy homeostasis is also present in human living environments and its principles and postulates also apply for electric power supply and consumption in such living environments [31,33,36,37,53–60].

Proposition 3.1.2.: Both misuse and excessive use of energy results mainly from inadequate electric power system regulations and the lack of choices and incentives to energy users to behave otherwise. Although environmental and lifestyle factors contribute to excessive use and misuse of energy, homeostatic adaptations to a more thrifty and efficient usage of electrical energy is possible and can be induced by voluntary energy consumption restriction while allowing others with greater needs to use such energy with economic benefits for all.

Proposition 3.1.3.: Thrifty and efficient use of energy and energy conscious-promoting environmental and systemic factors, regulations and services, along with homeostatic control systems employing reactive and predictive homeostasis, can be employed to regulate power supply and consumption more efficiently, thus avoiding energy overconsumption and waste. This can contribute to create the conditions for adequate choices and incentives to energy users to behave more thriftily and efficiently in their use of electrical energy, perceiving benefits and incentives for their actions, while allowing electric utilities to profit from such conditions [31–37,53–60].

Corollary.: The above propositions are supported by the following mathematical equations which represent the homeostatic control model being proposed here, which incorporates both predictive homeostasis (PH) and reactive homeostasis (RH). The expression for the energy equilibrium of the SES is given in terms of the total power supply and the homeostasis regulation mechanisms discussed previously:

$$E_{equib} = P_{supply}(x)PH(u)RH(v)S(\alpha) = E_{consump}(u, v, \alpha) + \frac{d}{dt}E_{consump}(u, v, \alpha)$$

$$\text{and } P_{supply} = RealPower + ReactivePower = (P + Q) - Losses$$

where x represents the internal state of the energy systems at time t_0 and Energy equilibrium E_{equib} is dependent upon several factors operating adequately in the SES. 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.

$S(\alpha)$ is the conditioning function of the SES and operates to alert and condition the HC system's adaptive mechanisms 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 system and the solution incorporates artificial intelligence and intelligent control. Thus $S(\alpha)$ is a function of adverse conditions and environmental challenges being sensed by the energy system and represented by the awareness and criticality variable α . All these three variables: u, v, α are incorporated as key constitutive elements of the intelligent algorithms built in the HC system and as such, are the equivalent of metabolic variables in living organisms like the physiological and endocrine systems' variables that affect the energy expenditure and storage of such systems.

3.2. The homeostatic Index and Grid_frac functions in the homeostatic control of SHES

The expression $\frac{d}{dt}E_{consump}(u, v, \alpha)$ stands for the rate of change of energy consumption of users, let's say a sustainable block [31–34] somewhere, and is a direct indicator of thriftiness and energy efficiency [34–41] being built in the SES. It is linked to powerful sustainability performance indicators of SES introduced previously in the literature, such as the homeostatic index H_i and the Grid_frac [33]. The homeostatic index is a powerful new concept previously introduced [33] which measures how much electricity is being drawn by each home from the mains as a percentage of the total electricity (renewable plus non-renewable) being consumed by the home [33]. This is being monitored and recorded in real time and shown to the consumer as a monthly reading or on a daily and hourly basis as preferred [32,33]. Essentially the homeostatic index is a measure of sustainability of energy systems. It shows how thrifty and energy efficient each home is with respect to the power supplied by the SHES (microgrid) and how much power is being drawn from the grid. Both the homeostatic index H_i and the Grid_frac functions are the workhorses that drive the energy system to higher levels of exergy in terms of the amount of energy that the energy source—the sustainable hybrid energy system (SHES)—can indeed deliver at any point in time, as well as the quality of said energy. This is important, not only because of what these two aspects of energy consumption management represent but also because they drive the exergy level being sought in the SES. We must not forget that exergy relates to the amount of energy that is available to be used in the energy system at any time. After the SES and the loads that are being supplied by the SES reach equilibrium, the exergy is zero [33,36,37]. What is different here from the traditional discussion on exergy available in the literature is the fact that exergy is not only an intrinsic quality of the energy source but it is also a variable which depends on the meta-system which includes the energy users in the sustainable block: A

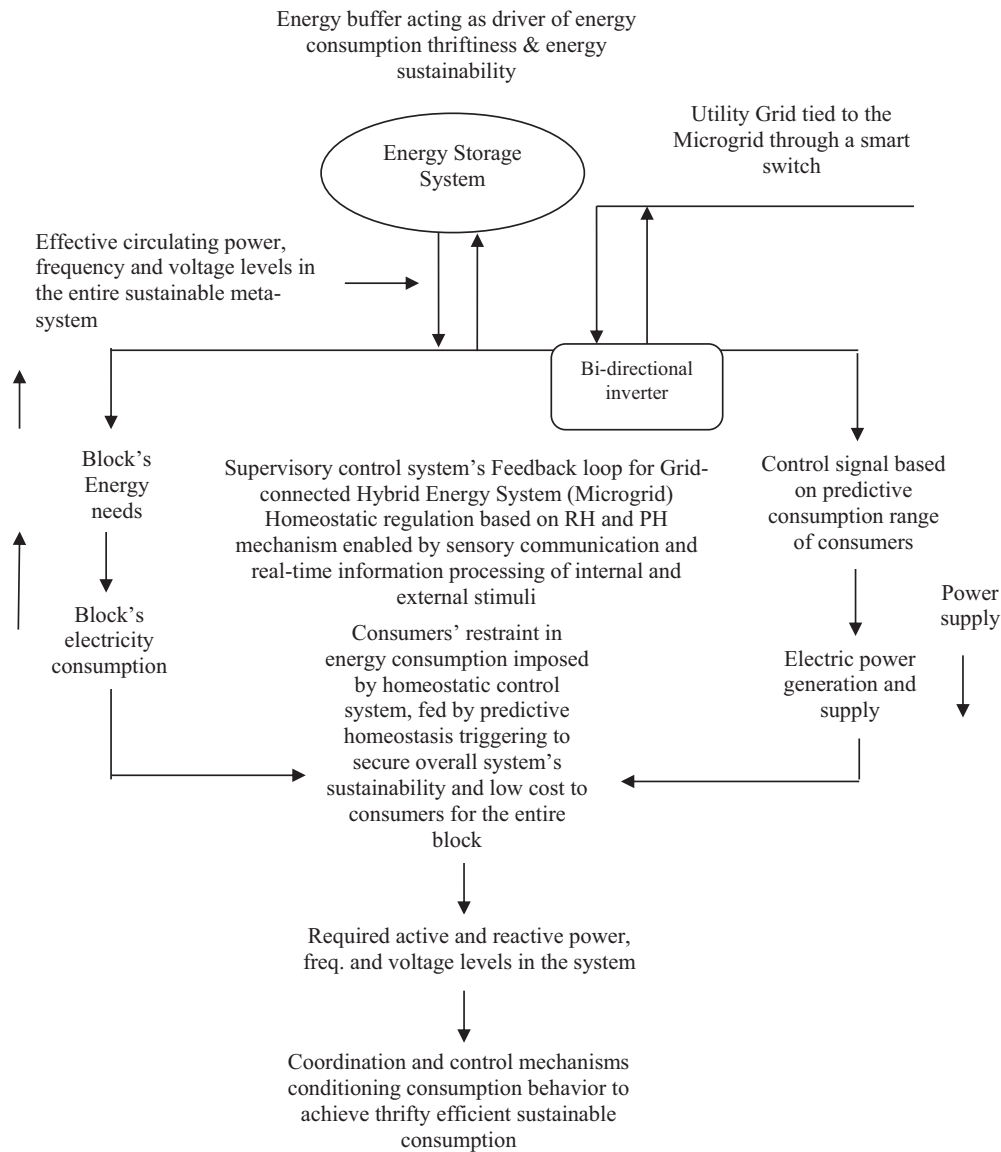


Fig. 2. Diagram of energy homeostatic regulation (HR) mechanisms in operation for grid-connected microgrid with an energy buffer. Source: Own elaboration. Source: Own elaboration.

value 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 EE for the home [33]. H_i represents a measure of the energy efficiency and thriftiness of energy consumers.

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 . Grid_Frac shows the fraction (in percentage) of the total electricity consumption drawn from the grid by each home in the sustainable block [32,33] (Fig. 2).

Below there is a diagram in Fig. 3 which illustrates the concepts presented here and which incorporates an Exergy index function which is related to the quality of the energy being produced by the SES and with the amount of thriftiness and EE being exercised by the users which directly impacts on

$E_{consump}(u, v, \alpha) + \frac{d}{dt}E_{consump}(u, v, \alpha)$ determining how much energy is being made available in the SES by the energy users of the sustainable block.

In the model depicted in Fig. 3 there is a particular homeostatic control (HC) and energy management architecture involving independent energy sources including an energy storage device and the electric grid. Here HC mechanisms trigger a system's sustainability stress

response that imposes a restraint over the energy consumption of the loads in the apartment building based on energy supply being available within the SHES. Both energy and exergy management are built in the SHES to enable resilience and sustainability [34]. The sustainability of the system is in part safeguarded by AI algorithms that make up the autonomous mission control of the SHES (microgrid). There is also an Exergy index function [34] that, like the homeostatic index, is a measure of the quality and efficiency of the energy being generated and utilized by the microgrid, which includes the energy consumers in the sustainable block (the loads). The higher the exergy index of the SHES, the higher its degree of sustainability and energy efficiency and by corollary, the lesser the dependence on the power grid [34]. The power supply by the SHES is adjusted based on the block's homeostatic regulation (HR) and exergy indices for the entire sustainable block based on peak aggregate demand of energy in the system throughout the day.

3.3. More traditional control methods of EPS and how the two may combine

The above control mechanisms come to complement more tradi-

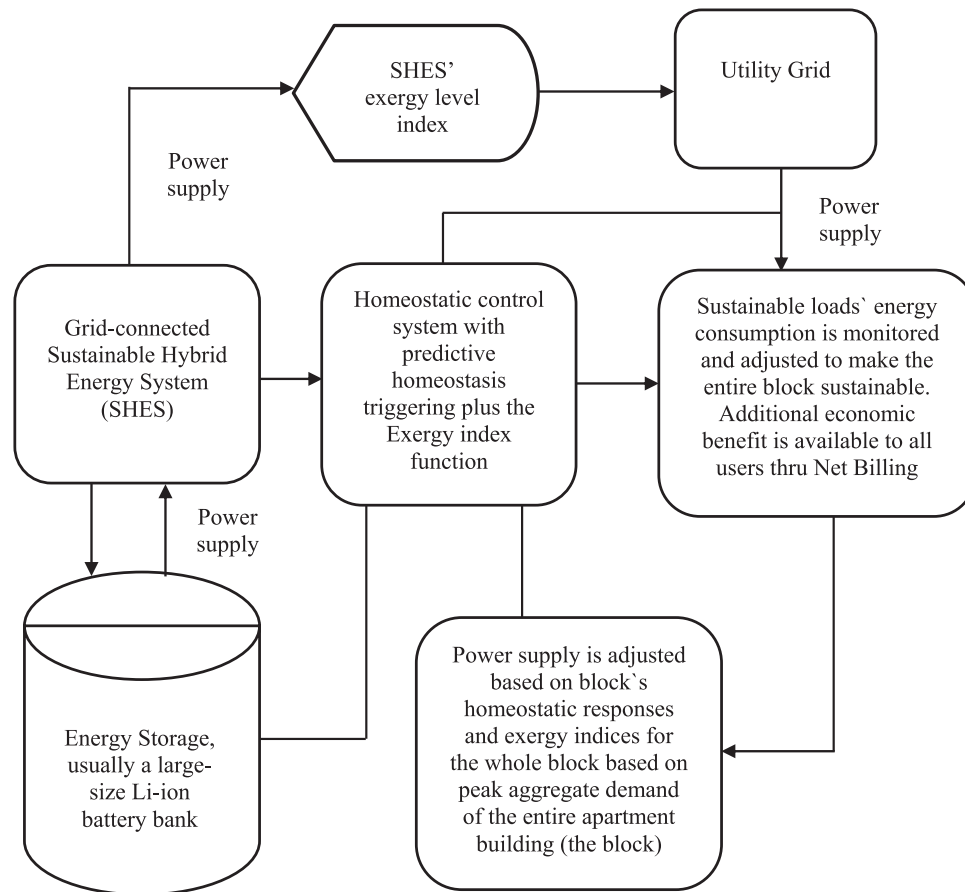


Fig. 3. Predictive and reactive homeostasis mechanisms operate as part of the HC of the SHES, this time with energy storage. Source: Own elaboration.

tional methods of control for EPS like the well-known droop control method. Traditional electric power generators are engines that drive a generator, whatever the type, providing a constant power output to meet the loads, with a power grid frequency and voltage level very stable for the most part. On the other hand, renewable energy sources like wind and solar systems which are part of SES solutions like the microgrid, have a variable output, depending on the wind speed or the local solar irradiation of the site. They require electronic inverters to interface with the system before supplying power to the loads. SHES like the microgrid require both, renewables and traditional sources of power generation to keep the system stable (unless connected to the grid) and capable of meeting loads' demand at all times. Depending on the size of these loads and the power consumption profile, there will be a need for more or less engine-type generation, combined with renewables and also with the grid when and where it is available.

When it comes to industrial power plants and large microgrids operating grid-tie, the power is mostly supplied by large rotating AC generators turning in synchrony with the frequency of the grid. The electric power grid system operates on a single frequency for all these generators and they must be synchronized in order to keep the system stable. If there is sufficient installed capacity in the system, that is, if there are enough generators to meet the loads at any given point, then the frequency can be maintained at the desired rate (i.e. 50 Hz or 60 Hz depending on country), otherwise the frequency will drop. When operating grid-tie, the phase angle of the power supplied by each generator in the microgrid will slightly lead the phase angle of the grid's power. This slight change in phase angle will be in correspondence with the power they deliver to the grid. An increase in the power demanded by the loads will result in an increase in the power supplied by the system's generators. In this case, the engines require more fuel to increase power yield, so the governor automatically opens a steam or

gas inlet valve to supply more power to the turbine.

However, if for some reason there is not enough capacity to meet the demand for power, even for a brief period of time, then generators' RPM and the frequency drops. For large power grids having large distributed loads and a number of good-size AC generators plus other sources of energy, like for example solar or wind, makes frequency management easier because any given load is a much smaller percentage of the combined capacity. For smaller grids like the microgrid, there will be a much larger fluctuation in capacity as delays in matching power supplied are harder to manage when the loads represent a relatively larger percentage of the generated power [61].

However, in addition to the above, a good HC system operating with adequate performance levels of EE and thriftiness can be used in order to impact the exergy of the system. This can help keep short-term fluctuations in power requirements 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 in 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 that more power is made available in the system for those that need more while others need less [34–37,39–41]. No doubt the changing frequency in the SES will influence the power flow but, at the same time, frequency is a function of the energy consumption being registered by the sustainable energy system, and the rate of change of such consumption as well, that is $E_{consump}(u, v, \alpha)$, therefore, employing the principle of demand response in energy management, power flow quality and energy sustainability of the energy system can also be influenced by

$$E_{\text{consump}}(u, v, \alpha) + \frac{d}{dt} E_{\text{consump}}(u, v, \alpha).$$

The difference in energy consumption will of course impact system's frequency and voltage level, which will ultimately impact the quality of the power supply and the overall system's dynamics in a sustainable energy system (SES).

With the droop method [65] the power angle depends heavily on the real power R generated while the voltage depends on the reactive power Q . If real power R can be adequately controlled, then so can the power angle, and if the reactive power Q can be regulated as well, then the voltage V_1 will be controllable too [62]. 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 [62]. The relationships between real power and frequency and the reactive power with voltage can be expressed as:

$f = (f_0 - k_p)(P - P_0)$ and $V_1 = (V_0 - k_v)(Q - Q_0)$ where k_p and k_v are the power and voltage droop gains respectively; f_0 and V_0 are the energy system's base frequency and voltage respectively, and P_0 and Q_0 are the set points for the real and reactive power of the SES at a given point in time and are subject to change as dynamic conditions evolve [62]. Reactive power regulation is used to impact voltage regulation and real power depends on frequency and phase angle, thus voltage will be controllable as well.

In the droop method, each unit uses the frequency, instead of the power angle or phase angle to control the active power flows since the units do not know the initial phase values of the other units in the standalone system. By regulating the real and reactive power flows through a power system, the voltage and frequency can be determined [62]. In the droop method, each unit uses the frequency instead of the power angle or phase angle, to control the active power flow since the units do not know the initial phase values of the other units in the standalone system [62]. Fig. 2 below shows a microgrid architecture model with several energy sources and loads.

4. Viewing and managing sustainable hybrid energy systems (SHES) like living open systems

The potential for using sustainable hybrid energy systems (SHES) as part of electric utilities' plan to decentralize the energy grid, as well as to further personalize or customize their vast services to their ample and diverse customer base, and to incorporate more localized DG solutions like the microgrid to be installed in buildings based on renewables, in tandem with the electric power distribution networks is part of the industry transformation in Chile which is being led by industry icons like ENEL. For this purpose, proper drivers for implementing such solutions are to be identified in each case as one size doesn't fit all. Particularly so in a country where there are ample differences in socioeconomic strata.

There are also distinct factors and conditions in the different regions of Chile that offer geographic potentials for production with the available technology and also the social and political support as well as the active involvement of the local community and authorities respectively. Therefore, to meet the energy requirements of both urban and rural communities, SHES stand as a viable and sensible distributed generation (DG) solution for electricity supply working in a smart grid configuration and operating with non-conventional renewable energies (NCRE) can be a viable and convenient solution to electric utilities' electrical energy distribution networks available. It can also be a much more convenient solution, both socially and economically, for the different regions and localities when, as it is the case in Chile, it is too expensive to extend AC power transmission lines and electric distribution networks thereof to connect new customers. However, the cost of hybrid energy systems based on renewable energy technologies (RETs) is generally high and there is also the problem of reliability associated with the NCRE due to their intermittent nature. Thus there arises the need to design and develop small, modular microgrid

systems like the SHES based on NCRE that are cost-efficient and economically profitable as an investment for utilities to widen their service pool.

Notwithstanding their small size and limited power generation range, which can operate in the kW range for residential purposes and also for small size industrial applications rather than in the Mega Watt (MW) range for power utility size application, there is always the back up from the mains to which the SHES is tied.

However, integrating renewables, particularly NCRE, requires a transition that for some communities may be much more difficult and complex than for others, depending on local socioeconomic conditions, availability of subsidies, and climate conditions due to their geographic location. The most pressing factor nowadays that is hindering such transformation towards a more widespread use of NCRE is the socio-economic and cultural characteristics of the communities. That is where the utility arises as an enabler and promoter of green electricity and efficient, sound and responsible energy consumption in order to create sustainable conditions for the country's growth and the well-being of a modern society like the Chilean, that is becoming more and more dependent on electricity. However, in every case, it certainly must mean an upgrade to something better than what they had before and to ensure employing the right energy policies and industry regulations that such improvements in living conditions and standards are sustainable over time [31,32].

Thus homeostatic control of SHES operated by electric utilities like ENEL that are tapping into the country's vast pool of renewables, the opportunity of employing predictive and reactive homeostasis control mechanisms have, no doubt, significant potential for contributing to the economic, social and environmental sustainability of a country like Chile. They also reduce emissions of local and global pollutants and may create local socioeconomic development opportunities for the communities to which they provide services as well [3].

4.1. An example of HC system installed in a SHES in the form of an electric utility's run microgrid for an apartment building community in Chile

The flowchart shown on Fig. 4 is an example of several HC algorithms. It depicts the management of the energy flow from a set of customers with distributed generation incorporated in an apartments building community in Santiago, through the use of a supervisory HC system which considers a storage energy unit operated by ENEL Distribucion (Fig. 4).

The flowchart in Fig. 1 represents the type of homeostatic control logic proposed in the paper which relates back to previous papers [3,31–37] on the subject albeit without considering predictive homeostasis as this one does. The example shown in Fig. 4 illustrates what is expected in real life once the homeostatic control (HC) system is installed by Enel Distribucion, along with the smart microgrids operated by them as well. The diagram shows the predictive homeostasis mechanism built into the system, which allows the utility to efficiently manage electrical energy in a residential building with smart metering. The building will have its own power plant with photovoltaic generation and energy storage. The different customers that integrate the residential community of the building are taken as one single unit (the entire block) for the local utility company in charge of distributing electricity whose rates present charges for energy consumed, maximum demand reached as well as maximum demand reached during peak hours.

The control strategy is based on the principles of homeostasis so that both the generation and supply on the one hand and the energy demand of the customers that comprise the residential block on the other respond to one another in an efficient and balanced manner, thus preserving the system's optimal efficiency and cost-effectiveness. This way it is possible to make compatible the grid-tied microgrid's supply capability with the users' demand through a system of compensation

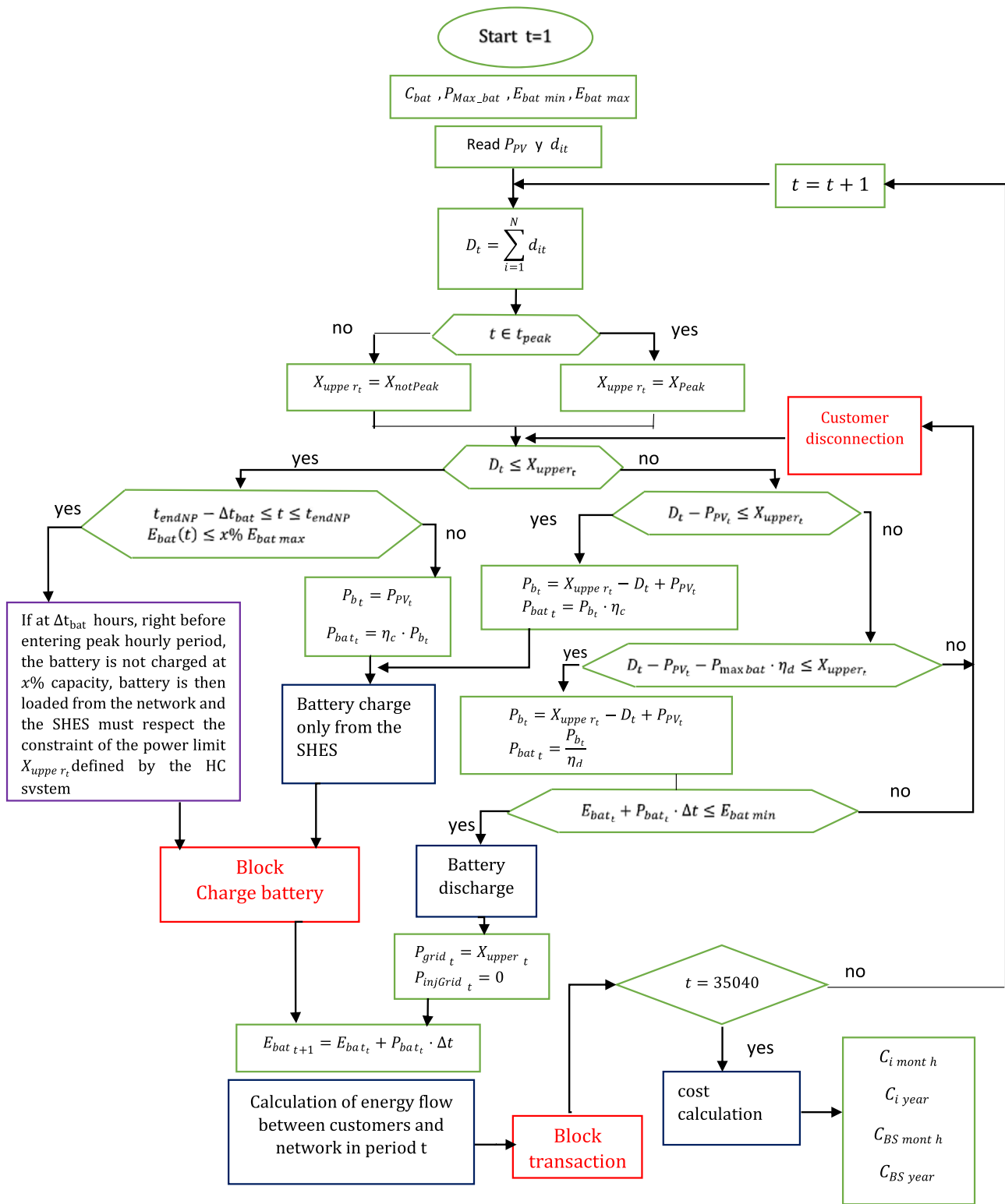


Fig. 4. Flow diagram that illustrates the supervisory control of electrical power supply and consumption to a set of residential customers through a particular control logic algorithm based on the principles of homeostasis.

among the different types of energy users. This allows those users that consume less (those who are thrifty, and seek to economize whenever and wherever possible, or else are more energy conscious in their energy consumption) in hours where the system is facing peak hourly demand (so called peak hours) to obtain an economic benefit or reward that is provided by those who require to consume more [32,33], in order to achieve a mutually beneficial arrangement between the parties,

that minimizes their social and economic costs [66]. At all times the SES seeks to maintain a state of stable and efficient equilibrium based on self-regulation of the meta-system, something that also benefits the electric utility and the energy distribution networks as a whole.

The control cycle begins with the battery, seeking to maximize the power generated by the battery, while observing the minimum and maximum energy levels of the battery charge cycle respectively.

C_{bat} , $P_{Max, bat}$, E_{batmin} , E_{batmax} . Then there comes the reading of the photovoltaic power available in the system and the energy demand of each home P_{PV} and d_i , respectively. Then the system calculates the total energy demanded by the sustainable block (D_i) and the energy demand limit of the sustainable block X_{upper_i} at this point in time, depending on whether it is during peak hourly demand period or not. If the total energy demand of the sustainable block is less than the block's demand limit $D_i \leq X_{upper_i}$, (both energy and power consumption are bounded by limits being set by the homeostatic control algorithms of the SES) based on the energy being produced by the microgrid and the energy available in storage at any point in time, all the photovoltaic (PV) energy generated will then be assigned to charge the battery $P_{b_i} = P_{PV_i}$ to its maximum charge limit.

The control module charge_battery is the energy manager in charge of charging the battery and handling its load while meeting all technical constraints of the same. The PV energy that cannot be uploaded to the battery because it either has already reached its maximum charge limit or because the battery is quite near its full energy storage capacity while demand is still strong, it will be automatically consumed by the users based on their energy consumption patterns which are registered by the HC system of the microgrid controlled by ENEL. At this time the utility will inform its customers of the supply surplus. In case the PV energy minus the energy destined for the battery is greater than the total demand $P_{PV_i} - P_{b_i} \geq D_i$, the remaining power is injected to the network according to the following $P_{injRed_i} = P_{PV_i} - P_{b_i} - D_i$. With this the customer obtains the benefit that the net billing system offers to the energy users in the community. ENEL is keen on introducing new, more personalized, flexible, and cost-effective alternatives for its millions of customers in Chile, and to expand the massive use of the net billing system and others to come throughout its vast customer base.

On the other hand if $D_i \geq X_{upper_i}$, the system will proceed to evaluate whether the demand of the sustainable block minus the photovoltaic power being produced is less than X_{upper_i} that is, if the condition $D_i - P_{PV_i} < X_{upper_i}$ verifies itself. If this is the case, the remaining PV power available is injected into the battery such that $P_{b_i} = X_{upper_i} - (D_i - P_{PV_i})$ observing battery constraints just as in the prior case. At the other end, when $D_i - P_{PV_i} \geq X_{upper_i}$, energy consumption will be drawn from the battery so long as the restriction of keeping the block's demand in the upper limit X_{upper_i} is met, that way the sustainability of the system is not compromised.

At this instance the system will assess if discharging the battery to its maximum discharge level (as permitted by the specified control system's constraints) is sufficient to maintain the demand's upper limit X_{upper_i} in check. If this is the case, the battery is capable of meeting the block's demand so the power needed is extracted from it in order to maintain said limit whereby $P_{b_i} = X_{upper_i} + P_{PV_i} - D_i$. The system then proceeds to verify if there is enough energy already in the battery. If this is the case then the battery discharging is done until the system's constraint is met. During this period the power supplied by the mains will be $P_{Grid_i} = X_{upper_i}$. In case the energy discharge of the battery is not enough to meet the power demand limit of the sustainable block, the system will discriminate according to the rules incorporated by design in the SES. Hence those customers who are demanding the greater power from the microgrid will be disconnected to favor the less demanding or thrifter ones. Thus they will only receive power supply from the utility's electric power grid, and this will go on until it becomes possible again to meet the control system's constraint that is $D_i - P_{PV_i} \leq X_{upper_i}$.

The transaction module is in charge of calculating the energy flows among the customers and the mains at all times. Thrifty customers with energy surplus can make this surplus available to those residents who consume more or else they can choose to allow this surplus to be injected in the mains, having the right in each case to an economic incentive defined by the utility which compensates their action. Of course they will be informed at all times of the economic benefit that

either one represents for them in terms of the money being saved from their energy bill, as a credit earned by the energy user. All customers are responsible for the loading and unloading of the battery alike, thus avoiding the decoupling that may be produced in time.

The battery is discharge during peak demand periods since the price of the maximum demand registered by the system in such periods is high. It is necessary that the battery is at its maximum capacity before entering peak hourly price period so as to respect the power limit defined by the control system, thus avoiding the disconnection of customers. The homeostatic controller that employs predictive homeostasis will then predict or anticipate the Δt_{bat} time in hours left before entering the peak hourly demand period, where the highest price for the electricity is charged to determine if the PV generation will be capable of charging the battery or not. If this were not the case the controller will then charge the battery from the mains observing the constraints both of the battery and that of the maximum power demand of the sustainable block $D_i \geq X_{upper_i}$. Δt_{bat} is the time needed for the battery to be recharged entirely to its maximum storage capacity and the x % will be adjusted empirically.

For simulation purposes, in order to illustrate the example shown here, once a year's worth of evaluation is completed by the system ($t = 35,040$, $\Delta t = 15min$) the monthly and annual costs of each customer are computed as well as that of the entire sustainable block.

4.2. Discussion

The concept of homeostatic control of EPS first introduced by Fred Schweppe and his team [53–60] back in late 1970s the early 1980s has been extended here, to include not only reactive homeostasis as first proposed by Schweppe and his team at MIT, focusing on HC of utilities. This time we also include predictive homeostasis (PH) mechanism operating in a meta-system which is comprised of the loads in an apartment building (the sustainable block), the utility grid and the DG solution in the form of a microgrid that constitutes the SHES. The meta-system being discussed here is all connected and operates with Net Billings, one of the recent advances in the law and regulation of the electric market in Chile. It is based on a future program being evaluated now by the utility company ENEL of Santiago, Chile, part of the ENEL Group, to implement this technology in buildings in Santiago in the future, with SHES being installed and operated by them. This joint venture initiative is circumscribed in a research project being carried out at the Universidad Tecnica Federico Santa Maria in Santiago with the support and participation of ENEL.

The HC system is part of the energy system (microgrid) which combines DG with the utility grid considering both options, with and without energy storage, in an apartment building and where all energy sources can contribute to make SHES more resilient, efficient and reliable while complementing more traditional control methods. PH involves a recursive set of mechanisms that trigger appropriate responses in the prospect of near future stimuli manifestation. In the case of sustainable energy systems, these constitute 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. 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. 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. 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 is a good example of such calamities, showing just how much chaos and destruction they can bring to its population. The February 27th 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, large fires extending to large forest and urban areas, and volcano eruptions, all of which cause havoc in our energy and communication networks.

The HC-based energy management system must respond to changes in the environment both in the immediate as well as in the short to medium term span. It must do so in such a way that its responses conform to sustainable community-driven HC strategies [3,31–37,53–63], that are best suited for particular environments and energy consumption schemes. Such strategies involve distinct homeostasis mechanisms that are aimed at preserving the efficiency and thriftiness in the energy supply and consumption process of the SES so as to ensure its well-being under any circumstance. Every energy system can only be truly sustainable and functional as a SES if and only if its internal mechanisms operate efficiently and opportunely as it is expected to occur in any healthy living system. It does so employing all means at its disposal (internal system's design engineering as well as the energy consumption management, e.g the loads) to attain optimal system's response to environmental conditions. This is true also in any living system that is made aware that there are enough resources available to it in the environment, so it can safely exercise restraint, thriftiness and energy efficient behavior without overdoing homeostatic regulation (HR) in a way that overstrains the system to a point where living conditions are compromised.

With the latter in mind, one can visualize that SES are moving towards the attainment of a new, safer and more sustainable equilibrium point—one that is conditioned by the sensory communication and information processing capabilities that are engineered into the SES itself, including the loads and their energy consumption characteristics [3,31–40]. Such capabilities can be enhanced and complemented by the presence of an energy buffer operating in the grid-connected microgrid. Being a definitely environmentally circumscribed artificial system, the SES in the form of an intelligent microgrid can only continue to exist and thrive so long as it is in continuous equilibrium with the forces that are internal and external to it. For this efficient equilibrium to exist and maintain itself under different circumstances, homeostatic regulation and adaptive energy consumption control must work coordinatively and flawlessly within a highly dynamic, real time environment whatever its characteristics may be. Therefore different options ought to be considered on how to engineer reactive and predictive homeostasis in SES design and later implementation, whether the microgrid is to operate tied to the grid or not. Such is the challenge to be analyzed for crating sustainable communities facing uncertain times. The characteristics of such communities behavior in terms of their use of energy and the goals that such behavior entail should certainly be considered in the design of HC systems for SES like the microgrid, and assess how the responses of energy users can be influenced by expectations and anticipatory behavior therein.

5. Conclusions

Climate change and natural disasters are a very serious threat that has brought worldwide attention and policy changes, increasingly so in the last few years. It is a harsh reality which demands concrete actions now, not later. World leaders have understood this and have been meeting for five years now, during the World Climate Summit (WCS) to discuss the matter in an effort to explore the possible mitigation measures. In WCS 2015 [67] which took place in Paris, France was

particularly relevant and important accords and measures emerged from this, which will hopefully bring about much needed changes in EPS infrastructure. 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 when it comes to natural disasters 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 with homeostatic control system, as is the case of SHES discussed here makes sense. The concept of energy hubs [41,42] is also part of this new power infrastructure vision with a much more sensible and reliable architecture than traditional energy matrix which relies solely on long transmission and distribution lines with exposure to the elements.

Furthermore, if we can equip these systems with adequate communications capabilities, AI and data sensing devices operating in interconnected fashion, in all systems comprising the power generation and distribution chain, this would make an even better solution based on Smart Grid technology available today. 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 more robust control system than 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 [22] (for cases in which a natural disaster strikes leaving a whole neighborhood without power), simpler, more efficient, flexible, economical and modular control solutions are possible [64]. This paper offers a glimpse of such new solutions, as part of a joint research and development project, incorporating reactive and predictive homeostasis control mechanisms to attain superior energy management and power supply and consumption control. These are part of the new frontier of control and communications systems engineering that will make possible for utilities to embrace DG and incorporate it into their product-service system supply.

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, including utilities, all of which is crucial to sustain any society's wellbeing and economic growth, little if anything has been done to counteract environmental and other threats (like vandalism and terrorist acts, for example) that put power supply stability at risk. Therefore a new model for SES is needed whose engineering design and homeostatic control capabilities incorporate reactive and predictive homeostasis. This new model may very well coexist and complement more traditional control and energy management methods like the droop control [65] to better equip the system with better environmental challenge management and resilience capacity. In general terms such capacity must extend the EPS functioning way beyond the perils that such systems have had to endure in the past, for example as a result of fault line power outages and abrupt shift in weather conditions for which they were originally designed. Unless the country takes seriously these challenges and upgrades its power grid looking at more modern options like SES with vast solar photovoltaic and wind penetration in the energy generation matrix [68–71] to complement its infrastructure, the effects of these calamities will continue to besiege the population of vulnerable countries like Chile,

Argentina and others in the world, affecting thousands of users each time for even longer periods than what has occurred in the past. Developing and implementing such a change in the country's power grid infrastructure will be necessary not only for the reasons already stated but also for diversifying and modernizing the power generation and distribution model as well. The latter has been understood and is beginning to be embraced by local utilities like ENEL which are currently considering employing DG solution in this endeavor. The work presented in this paper is part of this new emerging trend in Chile and is supported by the most important local electric power distribution company ENEL Distribution in Santiago, Chile. In the work to come we will show the simulation analysis of said project.

Sustainability and systems resilience can also be built through homeostasis control mechanisms engineered in EPS [3,32,33] that can promote and potentiate energy efficiency, thriftiness as exergy drivers, thus making the energy system more capable. The aim is for users to be able to respond to HC strategies designed in the system to further increase its resilience and adaptability capacity in the face of an environmental challenge like a natural disaster. Such systemic initiatives can complement well other measures that may be taken by local authorities and by the utility agents to better prepare the community for these occurrences. The benefits of the action scheme proposed here can be better realized and measured by the shared responsibility of the different parties involved, unlike the traditional scheme of the past to which we have been accustomed to for so long.

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