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Engineering Sustainable Energy Systems: How Reactive and Predictive Homeostatic Control Can Prepare Electric Power Systems for Environmental Challenges

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Abstract

Nowadays 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 and operational issues. They are required to respond to such challenges very rapidly and effectively so as to preserve stability and continuity of operations at any time, regardless of what may occur in the surroundings. This in fact is the true measure of what sustainable energy systems (SES) are all about, and homeostatic control (HC) of energy systems seeks just that: to enable energy systems to become highly efficient and effective very rapidly, by attaining a state of equilibrium 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) 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 its very essence—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. In this paper we present the groundwork that supports the theoretical model underlining the engineering of homeostasis in SHES. Homeostasis mechanisms are present in all living organisms, and thus are also applicable to EPS in order to enable and maintain a sustainable performance when EPS 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. 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 which anticipates the 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 concerns. The paper explores both concepts based on previous work in order to advance the research in the field of HC applied to electric power systems.

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1. Introduction

Ever since Cannon first formulated the concept of homeostasis, over 80 years ago [1,2] attention on homeostasis has been largely focused on its role in medicine and biology to find cures for diseases like diabetes and obesity for example, where research focused chiefly on the corrective responses and metabolic changes initiated after the steady state of the organism is perturbed. However, the concept of homeostasis, as important as it is in medicine and biology, has also been applied to Electric Power Systems (EPS) research [3-20], and in fact it should be extended, not only to include reactive homeostasis (RH) but also predictive homeostasis (PH) so as to understand the precise HC mechanisms that can be designed to enable a sustainable energy system to predict when environmental challenges are approaching or are most likely to occur and anticipate their impact early on in a recursive manner [3-10]. Sustainable energy systems (SES) encompass both reactive and predictive homeostasis operating recursively and proactively, in coordination with one another, in the face of an environmental challenge or some other system's issue which may raise concern. Reactive homeostasis (RH) in SES, as the name suggests, is a feedback-enabled mechanism driven by energy generation and supply versus energy consumption or expenditure. This can be engineered in EPS by employing sensors, control limit actuators (for example set-point fired responses) as well as AI algorithms that allow the system to make decisions when and how they are needed, in order to respond to changes in a predetermined array of the system's control variables. Thus whenever necessary, HC engineered in SES enable the energy system to take the actions required to counteract or fend off adverse conditions and noise which may affect the system's normal operation [3-20].

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 early on, anticipating predictable or very likely environmental challenges or some other glitch in the system. 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 effectively with sufficient anticipation. Such actions may come in several forms and will depend on the resources and intelligence built into the energy system, but they are all geared towards making the EPS more secured and able to withstand the upcoming challenge or threat by activating its readiness control mechanisms. Actions may come differently in magnitude and timeliness; some may be big and swift, aiming to adjust parts of the SES operation, while others may come more slowly and gradually, 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, how they will occur and under which conditions and circumstances, as well as where and how big will they be, will all be determined by both RH and PH control mechanisms designed and engineered in the EPS. Some may come very soon, while others may come at a longer time in anticipation of a probable environmental challenge [5-10].

Natural disasters, like earthquakes, volcano eruptions, and violent weather phenomena that we have seen happening more often in recent years, such as prolonged periods of intense rain and snow are nothing new indeed. On the contrary, with climate change on the rise, weather patterns are becoming more menacing, bringing strong winds and torrential rain out of the blue. Although such phenomena are not uncommon to humanity, they have become more recurrent and harsher in some parts of the world, like North and South America. 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, roads, electric power transmission and distribution, and telecommunication services are a vital part. Yet they are increasingly vulnerable when faced with such pervasive phenomena. 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. 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 epicentre 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. Yet, in spite of the latter, the country remains largely unprepared against massive water, telecommunication and electric power systems brake-down. The problem lies, as we all know, in the high percentage of centralized electric power and telecommunication systems that encompass large metropolitan areas like Sao Paulo, Rio in Brazil, Buenos Aires Argentina or Santiago in Chile, and also in the lack of adequate technologies and back-up/emergency EPS for disaster recovery when environmental threats or natural disasters befall [3,4].

2. Homeostasis-based energy management system for sustainable hybrid energy systems (SHES).

Homeostasis consists of a strategy in which power supply and energy demand (customers) respond to each other in cooperation so as to achieve mutual economic benefit and, at the same time, the community of users strives to keep the SES in a stable, efficient and self-regulated equilibrium. The diagram in figure 1 depicts reactive and predictive homeostasis mechanisms engineered in the homeostatic control of the SHES to be installed in an apartment building in Santiago, Chile by the local electric utility. In the diagram there is no energy storage and the grid operates as back-up. We extend the concept of homeostatic control to include not only reactive homeostasis (RH) but also predictive homeostasis (PH) which involves a recursive set of mechanisms that trigger appropriate responses in the prospect of near future stimuli manifestation. In the case of SHES, these constitute a set of corrective responses initiated in anticipation of a predictable environmental (both internal and external) challenge. In general terms, PH is an anticipatory response to an expected challenging event that may threaten the sustainability of the energy system in the near future. Electric utilities like ENEL Distribucion in Chile are studying the possibility of installing hybrid electric power systems [HEPS] like the microgrid, using both renewable energy technologies (RET) and conventional power generation units. This is part of an ongoing effort by ENEL Distribucion of Chile to expand the use of renewables and to explore the incorporation of DG systems in apartment buildings being serviced by ENEL, one of the main electric power distribution utilities in the country. With several decentralized power generation plants and distribution networks, a smart microgrid, powered for example by several Combined Heat and Power (CHP) units, can disconnect from a grid experiencing a power outage and continue to operate free of disruption until the main power grid is back online [19]. The SHES may be portable or fixed in one place, but it must be a highly reliable, easy to assemble, modular, flexible and cost-effective solution, that is ready-to-run and go to where it is needed in order to supply power if a natural disaster were to strike [3,4].

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. However, both predictive and reactive homeostasis must be in equilibrium and perfectly synchronized in the EPS, otherwise 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. As an example, the system shown in Fig. 1 is designed to efficiently manage power in an average residential building with intelligent metering, photovoltaic generation and no energy storage, just operating grid-tied. The different customers of the building will be considered as a single client conforming a sustainable block [3-10] for the local electricity company. The agent in charge of managing the energy flow will be a supervisory control system based on homeostasis mechanisms built into the system in the form of software (intelligent algorithms) and hardware that allow to determine the best option for purchasing electricity that the customer has available at any time, provided by the power distributor and to capture an efficiency in conjunction with the internal optimization of the micro network in order to finally have an optimal electric distribution system in terms of cost versus service. The model shown involves managing the energy flow of a set of clients with distributed generation of electricity by using a supervisory control that may or may not consider an energy storage system. The analysis focuses on modeling and simulating a distributed generation (DG) solution in the form of a small microgrid for residential use that is managed by the electric utility ENEL Distribucion. The microgrid offers a more cost-effective, more independent and flexible local alternative to the power grid, which aside from complementing the grid, provides a more efficient technical and economic energy management scheme of the energy supply, optimizing energy consumption with exergy maximization consideration between non-conventional renewable sources and the power distribution network [3-10].

2.1. Engineering reactive and predictive homeostatic control in hybrid electric power systems(HEPS).

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 [3-10]. Sustainable energy systems encompass both reactive and predictive homeostasis operating recursively and in coordination with one another in the face of an environmental challenge. Reactive homeostasis (RH), 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 the right decisions in response to changes in a predetermined array of the SES 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. The sustainability of the system is in part safeguarded by AI algorithms that make up the autonomous mission control of the microgrid.

2.2. The role of exergy, energy efficiency and thriftiness in the design and engineering of SHES.

There is also an exergy index function [5,6,7,9,10] that, like the homeostatic index [6,7], is a measure of the quality and efficiency of the energy being generated and utilized by the microgrid system including the energy consumers in the sustainable block (the loads). 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 SES. 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. Thus 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 [3-10].

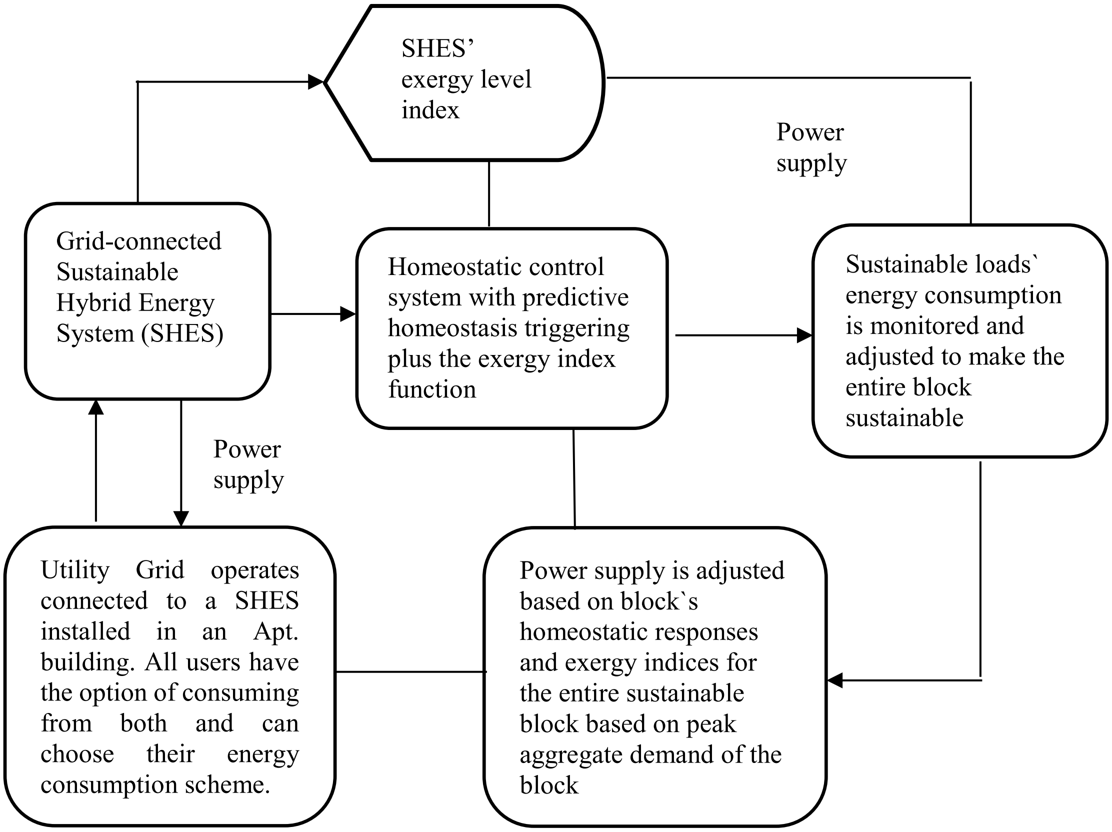

Fig. 1. The diagram illustrates how homeostatic control mechanisms based on reactive and predictive homeostasis trigger a system's sustainability stress response that imposes a restraint over energy consumption of loads based on the energy supply being available in the SHES. Source: Own elaboration.

As an example, in the model depicted in Fig. 2 below there is a particular control and energy management architecture involving independent energy sources as part of DG plant tied to the grid. This example shows how a particular energy consumption criterion allowed and managed by the utility grid operator can enable and foster sustainability in the SES while providing benefits to all. Here both energy and exergy management are built into the SES to enable resilience and sustainability [3-10]. Likewise, Fig. 3. shows a diagram representing a HC model which illustrates a potential microgrid architecture with several energy sources and loads [20].

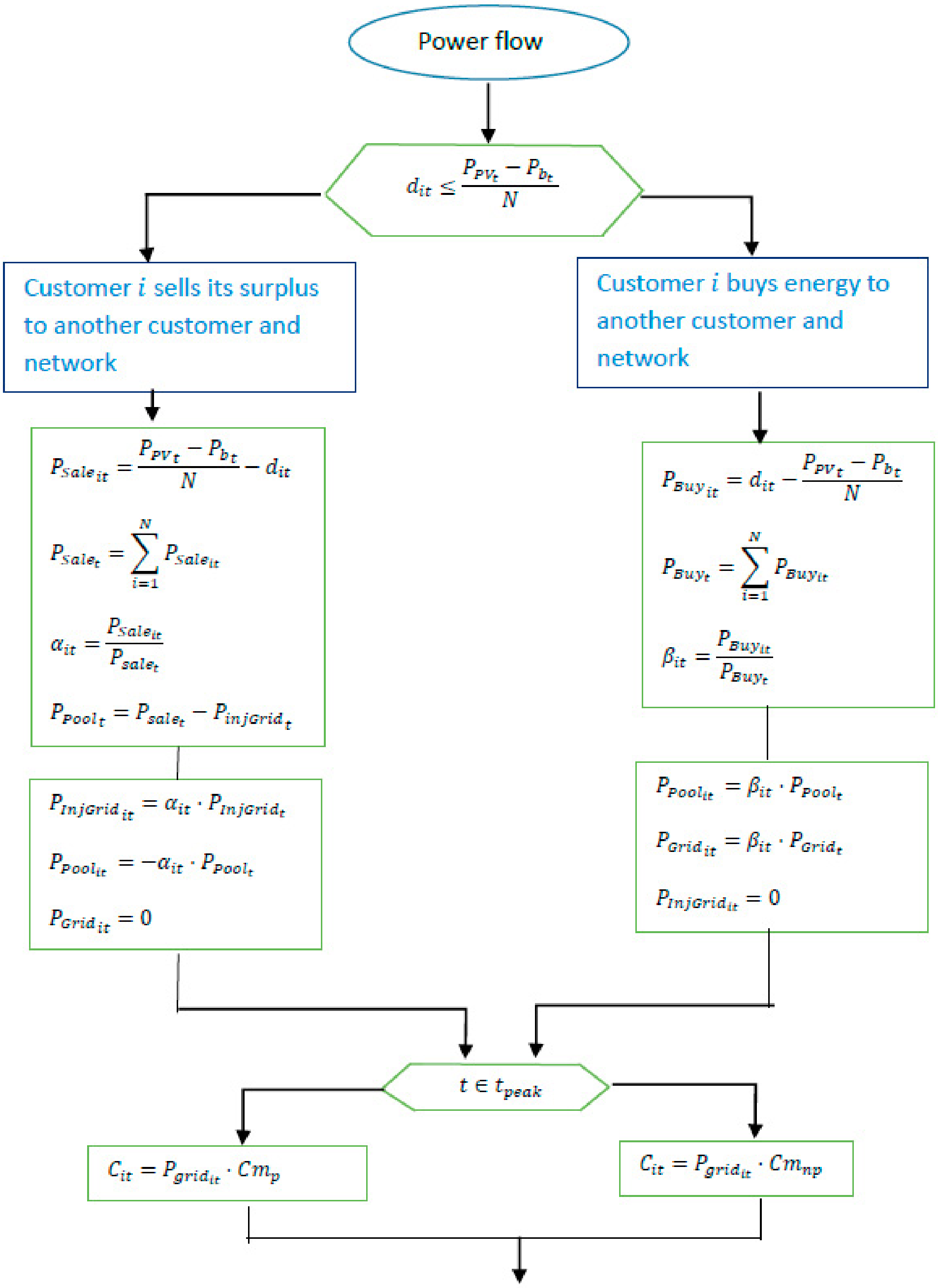

Fig. 2. Above it is shown a particular criterion based on (homeostatic control) HC which permits the energy exchange between the utility's customers and the electric power distribution grid. Source: Own elaboration.

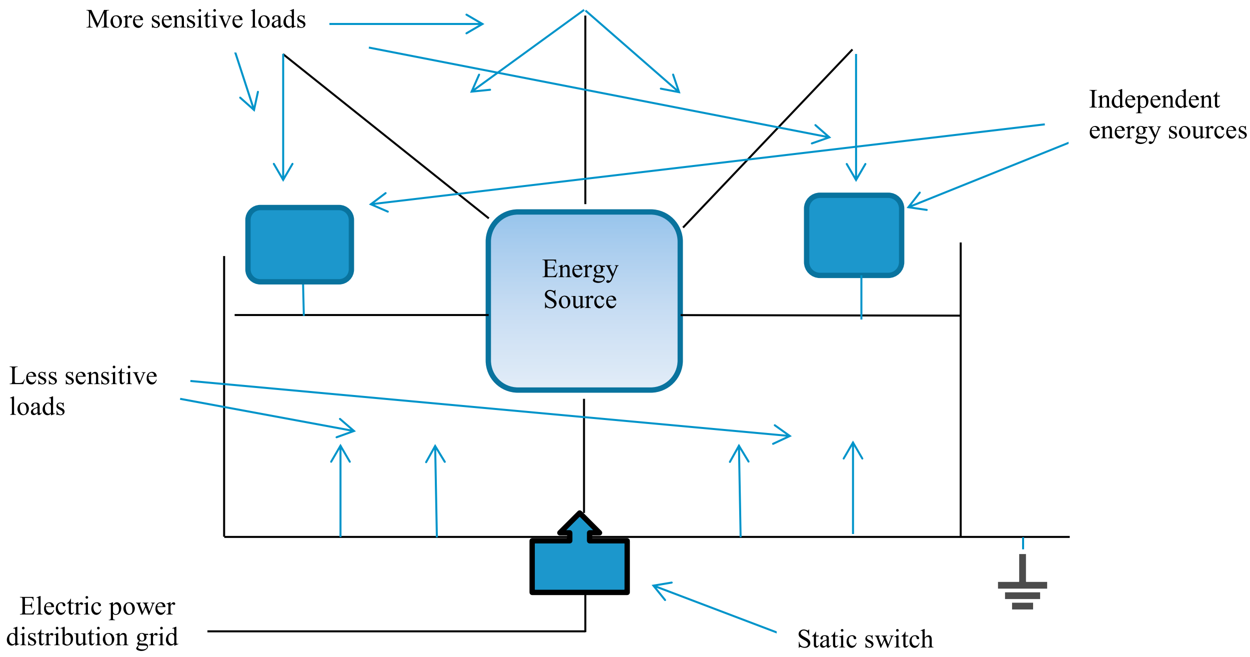

Fig. 3. A diagram representing a HC model which illustrates an example of a potential microgrid architecture with several energy sources and loads. Source: adaptation of Fig. 1 in “Microgrid concept (Electrical point of view)” [20].

3. Conclusions

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 strong winds, sudden heavy snow in places that never see any snow like Santiago, as well as earthquakes and floods, all of which are part of the vast arsenal of natural disasters and other dangerous phenomena affecting modern infrastructure and threatening mankind’s modern way of life just about everywhere [3,4]. Smart microgrids can supply electricity and potentially heat to residential and office building communities in large cities like Santiago, where a strong rain or heavy snow overnight can leave thousands without electricity and heat for up to 72 hours. Hence utility’s installed DG with renewable energy technologies (RET) and CHP is not a bad option when we are living at times of unpredictable twists in climate and other natural disasters, in which all of a sudden a natural event can strike out of nowhere with furious force, leaving a whole neighborhood without power, in complete and utter darkness. Such calamities may expose the population to chaos, and danger of rampant looting and other crimes, plus perils of all sorts. We need to have less vulnerable, more flexible and resilient electric power systems as part of our electric utilities infrastructure, as the next disaster will come for sure. But when? That we don’t know. What we do know is that we ought to be ready and well prepared for it, otherwise we will continue suffer at the expense of the capriciousness of nature and the unpredictability and absurdity of human error, especially in our most critical systems like electricity, water and communications.

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