Energy Security and Sustainable Development Implications for Guatemala of the Electricity Generation Expansion Plan 2014-2028

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Master thesis in
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Abbreviations

GWh	Gigawatt-hour (measure of electrical energy = 10^6 watt-hours)
kWh	Kilowatt-hour (basic unit of electrical energy = 10^3 watt-hours)
MW	Megawatt (unit of electrical power = 10^6 watts)
MJ	Megajoule (unit of energy = 10^6 joules)

Energy security and sustainable development implications for Guatemala of the Electricity Generation Expansion Plan 2014-2028

KAREN OCHAETA

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Abstract: Electricity consumption in Guatemala has been steadily increasing during the recent years, challenging the generation sector to keep up with the pace of electricity demand in the long term. To tackle this problem, the government of Guatemala has delineated the Electricity Generation Expansion Plan for the period 2014-2028, proposing several hypothetical future scenarios of the energy mix for electricity production. The aim of this thesis is to evaluate how the fulfillment of this plan would influence energy security and sustainable development prospects in the country. Following an assessment framework that allows a systematic evaluation of the system, indicators that reflect potential vulnerabilities and sustainability concerns are applied to the scenarios. The results show that energy security in the electricity sector could increase as a consequence of the capacity expansion and transformation of the energy mix to rely more on indigenous sources, taking into consideration scenarios with a more diversified portfolio that include the expansion of biomass and geothermal capacity to compensate for the vulnerability of hydroelectricity to weather events. The prospects for sustainable development in the country can be supported by the provision of secure electricity supply that takes into account efficiency and mitigation measures in the exploitation of natural resources, as well as social impact assessments to ensure that the plan will not affect the livelihood of vulnerable groups and has the possibility to contribute to increase equity in electricity access.

Keywords: Sustainable development, energy security, energy mix, electricity generation, electricity access, economic development.

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Summary: Electricity is a key element that touches almost every aspect of modern societies and plays a crucial role in providing essential services such as access to effective health and sanitation facilities. This is especially relevant in developing countries, where insufficient capacity and low access hinder economic and social development. Recognizing these challenges, the government of Guatemala is promoting the Electricity Generation Expansion Plan 2014-2028 as a part of a strategy to upgrade the whole electricity system and fulfill the growing demand.

The purpose of this thesis is to give insights of the implications of the fulfillment of this plan, taking into consideration aspects of energy security, environmental sustainability and socioeconomic development. Since the expansion of generating capacity involves not only the optimization of current infrastructure, but the transformation of the energy mix, it is important to evaluate how this change would affect security of electricity supply and sustainable development in the country.

An assessment framework is used to evaluate the expansion of the generation system. It starts with defining energy security in the context of electricity supply and taking into account the objectives of the country's energy policy. In this context, priorities like provision of reliable and affordable electricity, decreased dependence on imports, increased diversity and access through the use of renewable sources, are emphasized. By understanding the connection between energy security and sustainable development, key aspects of both perspectives are established: adequacy, resilience, and sovereignty dimensions of energy security, and economic, social and environmental dimensions of sustainable development.

The delineation of the electricity generation system is the second step to specify the system's boundaries and the characteristics of their elements. The third step consists on the identification of vulnerabilities and sustainability concerns in order to translate them into measurable aspects of the system, that is, quantitative indicators. The final steps include the application of those indicators to each energy mix alternative provided in the generation expansion plan and the interpretation of results. These results show that the sovereignty concerns are addressed by decreasing reliance on imported fuels, but the adequacy and resilience of the system may be compromised by an unbalanced energy mix dominated by hydroelectricity generation.

Potential reductions in electricity costs and expansion of electrification coverage address economic and social concerns regarding sustainable development. The environmental aspect is measured through the share of renewable energy in electricity generation. Higher proportions of renewable sources on the future energy mix can reduce environmental impacts in relation to the energy mix of 2013, by avoiding pollution related to fossil fuels combustion. However, mitigation measures need to be taken into consideration as the exploitation of renewable sources raises environmental concerns as well. The capacity expansion of coal-fired power plants could change the proportion of electricity generated from this source in the future, raising environmental concerns.

Keywords: Sustainable development, energy security, energy mix, electricity generation, electricity access, economic development.

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1. Introduction

Access to modern energy services is crucial for raising living standards, improving social and economic well-being and reducing poverty by contributing to the attainment of many of the Millennium Development Goals (IAEA, 2005, IEA and OECD, 2010). The electricity sector in particular, plays a key role as most economic activities rely on assumptions of reliable sources of electricity (Krishnaswamy and Stuggins, 2007), making energy security a priority in policy making (Cherp et al., 2012).

Guatemala, a developing country that is emerging from a civil war that lasted 36 years and with more than 50% of its population living in poverty (The World Bank, 2012a), faces social and economic challenges that cannot be overcome without improving electricity access to support the provision of basic services and boost labor productivity to build up the human capital. In accordance with this, the Ministry of Energy has proposed the expansion of the electricity generating capacity to meet the increasing demand while reducing dependency on oil products, diversifying the energy mix from fossil fuels to renewable sources, and reducing electricity costs (MEM and CNEE, 2009).

Pursuing cost optimization in the energy sector provides opportunities to improve social capital, but sometimes neglects the identification of unsustainable resource use patterns (Valentine, 2010). Moreover, increasing energy intensity and reliance on electricity services make societies highly vulnerable to any supply disruption (Cherp et al., 2012), demanding thus better strategies to enhance security of electricity supply. By understanding the role that secure electricity services have in improving socioeconomic conditions and the characteristics of each energy source considered in the expansion plan, this thesis focuses on assessing the modifications to the power generation system from both energy security and sustainable development perspectives following as assessment framework proposed by Cherp and Jewell (2013).

The energy security assessment framework aims to evaluate a specific energy system in a systematic way allowing identification of context-sensitive vulnerabilities (Jewell, 2013). In this thesis, the framework has been extended to cover aspects related to the three pillars of sustainable development: environmental sustainability, economic and social development, and is divided into five stages: (1) defining energy security for the purpose of the study, in order to provide a conceptual framework that guides the rest of the assessment (2) delineating vital energy systems to understand the dynamics and key aspects of the system under study, (3) identifying vulnerabilities and concerns that can be expressed in quantitative proxies or indicators, (4) selecting and calculating indicators, and (5) interpreting the indicators.

1.1. Problem definition

The Electricity Generation Expansion Plan for the period 2014-2028 has been outlined by the Ministry of Energy through the National Commission of Electricity (CNEE) (MEM, 2013a). It encompasses the transformation of the energy mix for electricity production as an effort to increase diversification of energy sources and displace oil products. Although the plan provides a set of scenarios according to different priorities and combinations of energy sources, it lacks a systematic and comprehensive analysis that identifies key aspects of security of electricity systems and implications for sustainable development of each alternative.

1.2. Aim and delimitations

Based on the plan elaborated by the CNEE and the different projections for energy mix that it portrays, this study aims to explore how its fulfillment would influence energy security and sustainable development in Guatemala. Following an assessment framework, each energy mix is analyzed through a set of indicators aimed at measuring aspects of energy security as well as economic, social and environmental sustainability.

Although the electricity supply system encompasses a large array of components and complex interactions, this study is limited in scope to the evaluation of the energy source mix for power generation. Due to the complexity of energy security and sustainable development challenges, the analysis is not capable of covering all of their related aspects. The indicators selected to evaluate the different alternatives are determined by the boundaries of the system under study, the identified vulnerabilities, and the availability of data.

1.3. Outline

This thesis consists of six chapters. Chapter 2 explains the main drivers behind the plans to expand the electricity generation system, as well as the goals of the Ministry of Energy to modify the current energy mix for electricity production. Chapter 3 describes the methodology for assessing energy mix scenarios under energy security and sustainable development perspectives. It provides the theoretical foundations to conceptualize energy security and to better understand the connections between security of electricity supply and sustainable development, along with the systematic evaluation of the electricity generation system based on its main characteristics. The indicators selected to assess the different scenarios proposed to increase the capacity of electricity generation are described in section 3.5. The results of applying the selected metrics to each of the energy mix scenarios are presented in chapter 4, followed by the discussion of results and conclusion in chapters 5 and 6.

2. Background

2.1. Guatemala's socioeconomic context and the electricity sector

With an estimated population of 15.79 million (INE, 2012), annual population growth rate of 2.4%, and GDP of US$50,236 million (CEPAL, 2014), Guatemala is the largest economy in Central America but one of the least developed and unequal nations in the Latin American region. The country's GDP is dependent on three main sectors: services, accounting for 62.7% of GDP and 48% of labor force, industry, representing 23.8% of GDP and 14% of labor force, and agriculture, which accounts for 13.5% of GDP and 38% of labor force (The CIA World Factbook, 2014). According to the United Nations Human Development Index (2013), Guatemala ranks 133 out of 187 countries, and is in the last place in Central America (The World Bank, 2014). 53.7% of the Guatemalan population lives under the poverty line and, from those, 13.3% live in extreme poverty. On the other hand, economic performance has been relatively stable in comparison to the rest of Latin American countries, and between 2001 and 2011 the average economic growth has been 3.3% (The World Bank, 2012).

Full integration of rural population in terms of economic opportunities and the diversification of the industry into higher value-added products and services are crucial aspects for Guatemala, since up to 51% of the total population (INE, 2012) and 80% of the extreme poor dwell in the rural areas (The World Bank, 2012a). This premise relies mostly on an economic perspective of sustainable development, in which shared prosperity and sustainable growth is attained through inclusive and environmentally sound policies over time and across generations (The World Bank, 2014). Although the term "sustainable growth" has been criticized as being contradictory in a world with ecological constraints (Hopwood et al., 2005), Rogers et al. (2008) argues that economic growth needs to be stimulated in poverty-stricken areas through the efficient allocation of resources in order to make progress towards sustainable development.

It has been recognized that access to modern energy services, understood as electricity and clean cooking facilities, and overall environmentally-friendly energy, are preconditions for sustainable development and poverty alleviation (UN-Energy, 2007). Electricity, in particular, plays a key role in enhancing human well-being by providing effective and reliable healthcare services, access to safe drinking water and sanitation facilities through water pumping, adequate illumination and telecommunication infrastructure among others (IAEA, 2005, UN-Energy, 2007). Lack of access to energy is a major constraint for achieving the Millennium Development Goals to halve the proportion of people living in poverty by 2015. Consequently, the UN Advisory Group on Energy has suggested that the goal of universal access to modern energy should be set by 2030 (IAEA, 2005, IEA and OECD, 2010).

In Guatemala, one of the infrastructure constraints is the electricity sector (The World Bank, 2009). It has undergone structural changes since its deregulation and the creation of the Electricity Law in 1996 (BCIE, 2009), allowing the participation of the private sector with significant investment in power generation and distribution infrastructure (MEM and CNEE, 2009). Figure 1 shows how electrification coverage, or the proportion of population with access to electricity, increased significantly from 35.8% in 1990 to 85.1% in 2006, with 71% of electricity produced by private power plants (CEPAL, 2013). Nevertheless, from year 2003 the pace of investment in generating capacity has not been sufficient neither to guarantee the balance between electricity supply and demand in the long term, nor to decrease the electricity price due to high dependence on imported oil products (MEM and CNEE, 2009).

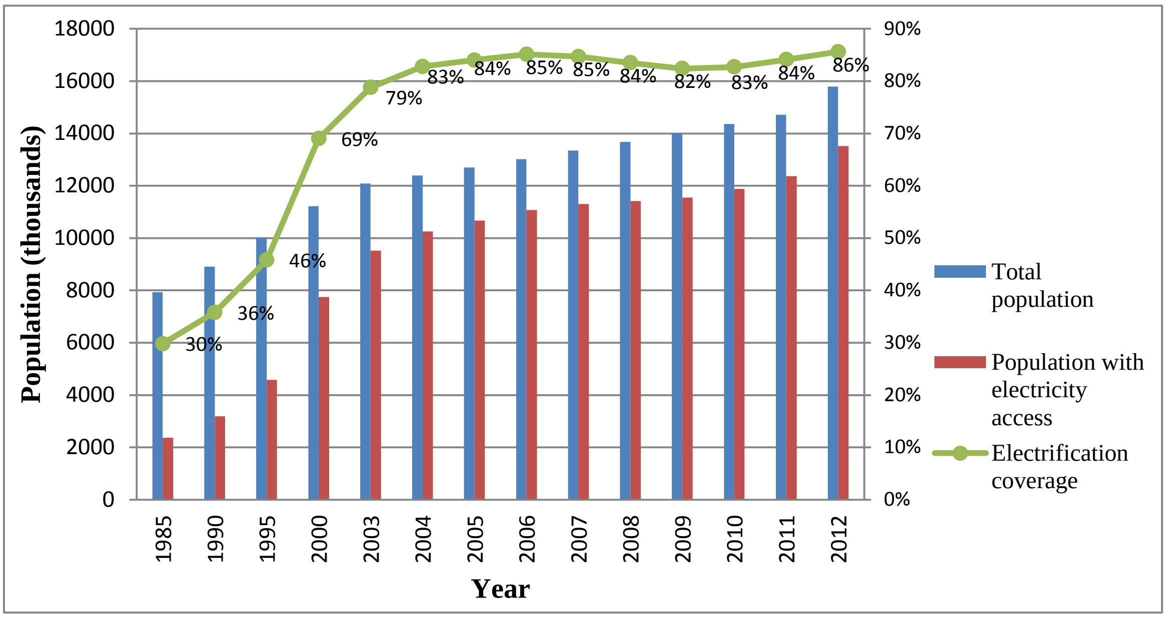


Fig. 1. Proportion of population with access to electricity in Guatemala from 1985 to 2012
Sources: CEPAL (2012), MEM (2012).

In addition, electricity coverage in the country is highly uneven; in the urban areas more than 97% of the population has access to electricity, while in some rural provinces only 35.6% of the population is connected to the grid (MEM, 2012). The government recognizes that increasing electrification rates in the rural areas represents a major challenge and has committed to increase the electricity access to 95% of the population by 2027 (MEM, 2013b).

Another challenge identified in the energy policy is the rising and volatile price of oil products, considering that the country is a net oil importer (MEM, 2013b). According to the country's statistical profile elaborated by the National Institute of Statistics in 2012 (INE, 2012), fossil fuels account for 70% of the total value of imports to the country. The same study further reveals that while diesel is the main imported product with a share of 29.9%, bunker oil or fuel oil, which is an important input for electricity generation, accounts for the 10% of value of the country's imports. According to the World Bank (2012), electricity price is one of the highest in the region because of high marginal costs of generation and due to the fact that Guatemala does not subsidize energy as heavily as other countries in Central America. Subsidies account for 71%, 56%, and 11% of the electricity price to users that consume a maximum of 50, 100 and 300 kWh per month respectively, regardless of the energy source (Santizo, 2011).

The situation mentioned above is one of the main drivers behind the governmental plans of increasing the share of renewables and non-oil sources for electricity generation. Currently, the mix of renewable energy sources for electricity production in Guatemala includes hydro, geothermal power, and biomass from sugar cane residues. In Figures 2 and 3 the share of each energy source for electricity generation and their installed capacity are illustrated. The proportion of electricity generated from renewable sources has varied significantly, from 92% in 1990 to 63% in 2013 (CEPAL, 2013, MEM, 2014). Fuel oil and diesel-fired thermal plants started to operate in the 1990s and coal-fired power stations have been increasing its installed capacity since the year 2010.

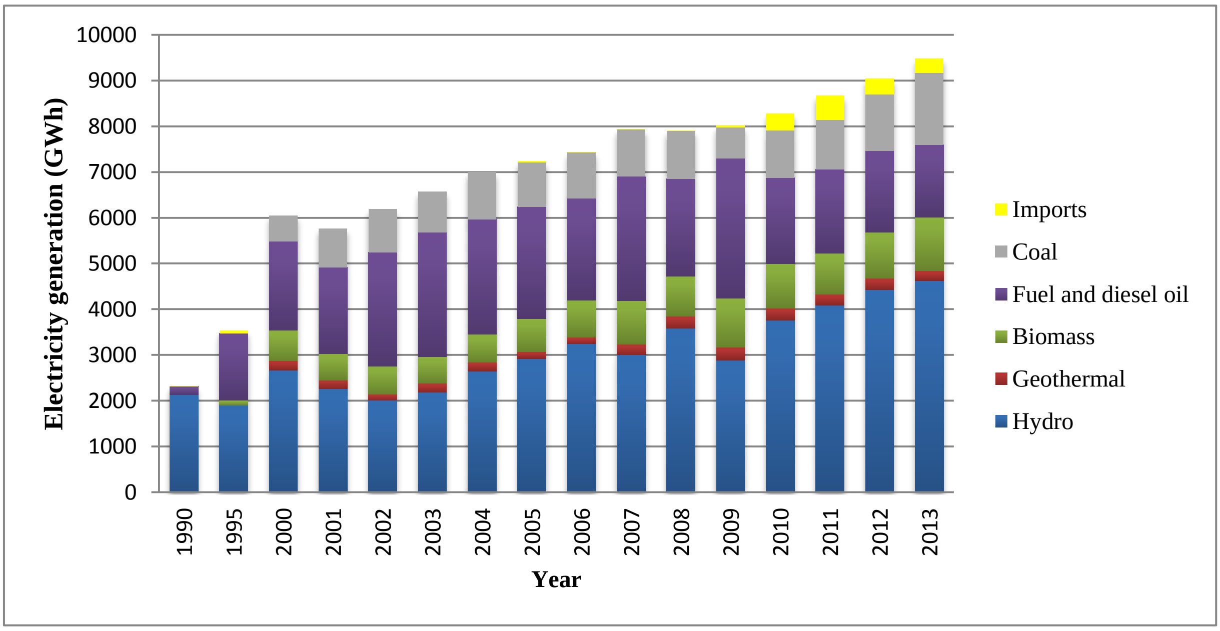


Fig. 2. Evolution of the amount of electricity consumed in Guatemala
Sources: CEPAL (2012), CEPAL (2013), (MEM, 2014).

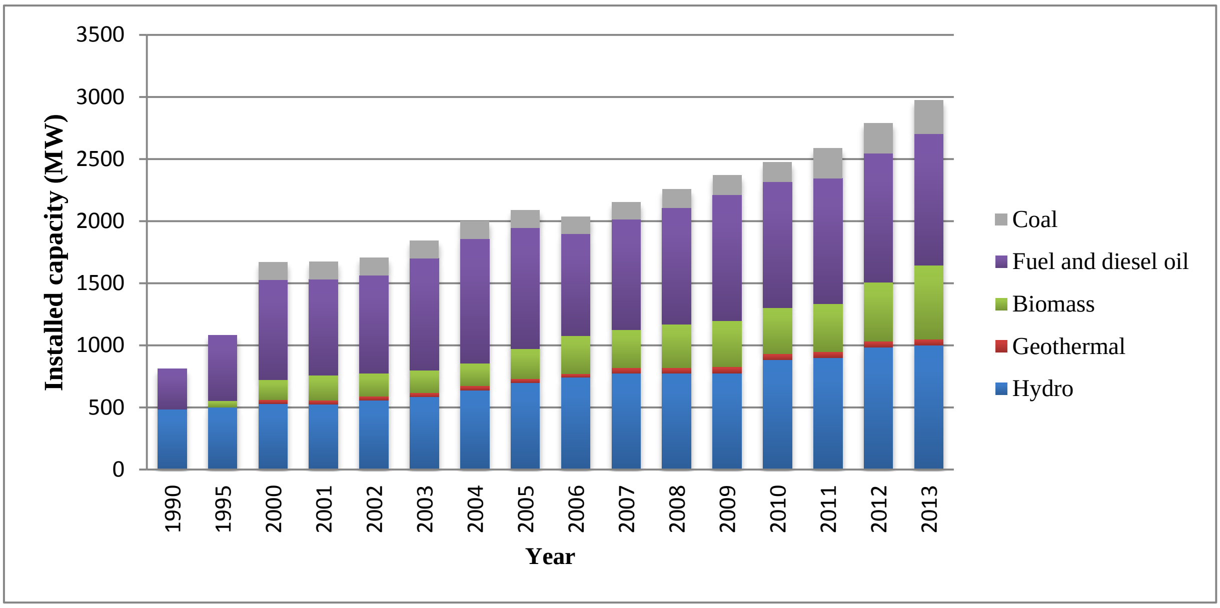


Fig. 3. Evolution of the installed power capacity in Guatemala
Sources: CEPAL (2012), CEPAL (2013), (MEM, 2014).

2.2. Electricity Generation Expansion Plan 2014-2028

In order to achieve self-sufficiency in electricity generation and become more independent of the fluctuating and rising price of oil, the government of Guatemala through the CNEE developed the Electricity Generation Expansion Plan 2008-2028 (MEM and CNEE, 2009), from now on referred to as the Expansion Plan, which was recently updated to cover the period 2014-2028 (MEM, 2013a). It is part of a strategy to upgrade the whole electricity system in the country. The first part of this strategy is addressed by the Transmission System Expansion Plan 2008-2018 (MEM and CNEE, 2009), in which the whole transmission system is being upgraded to support the increase in generating capacity from renewable and non-renewable energy and reduce transmission losses and operational costs. According to the CNEE, future savings due to the improvement of the transmission grid will outweigh its investment costs (MEM and CNEE, 2009). The Expansion Plan's objectives, which are in line with the country's energy policy goals, are: diversification of energy mix, increasing the installed capacity of renewable sources to at least 67.5%, attract investment to expand generation from geothermal sources, optimization of resources and increased efficiency in electricity generation, reduction of electricity costs and prices, and reduction of CO_2 emissions (MEM, 2013a).

In view of the significant renewable energy potential that the country has in the form of hydro, geothermal, wind, biomass and solar (MEM, 2013b), the CNEE considers the possibility to displace fuel and diesel oil-based thermal power stations (MEM and CNEE, 2009). Guatemala has an area of 1,568 square kilometers where wind power is categorized as class 4 or higher, geothermal potential due to the existence of 36 volcanoes, and mountainous topography that increases the feasibility of hydroelectricity projects (MEM, 2013b). Table 1 shows the energetic potential of different resources as published by the Ministry of Energy in the energy policy.

Table 1. Guatemala's energy resources and their potential

Energy resource	Estimated installed capacity	Current production (2013) in relation to the estimated installed capacity
Hydro	6,000 MW	15%
Geothermal[1]	1,000 MW	5%
Wind[2]	280 MW	0%

[1] The estimated capacity in identified fields accounts for approximately 30% of this potential (The World Bank, 2012b).
[2] Other assessments based on the Solar and Wind Energy Resource Assessment maps, developed by the United States Department of Energy, estimate onshore wind installed capacity of 7,840 MW (GENI, 2012, SWERA, 2012).

Guatemala's positive aspect in terms of exploiting its renewable sources of energy is that the site of the sources is relatively close to the main load centers, meaning lower costs to integrate them to the transmission grid (Koberle, 2012). Taking into consideration the scale of production in the country, studies have shown that hydro and biomass power plants can generate electricity at competitive prices with fossil fuel-based plants; other technologies based on wind and geothermal power are promising, but at small scale, like are currently projected, still present some disadvantages in economic terms (BCIE, 2009). A comparative analysis of electricity generation costs in the Central American region places hydroelectricity from small-scale plants as the most competitive option in economic terms (0.019 to 0.022 US$/MJ), compared with electricity generated from fuel oil-fired power plants (0.033 to 0.042 US$/MJ), assuming 2010 oil prices, and with coal-fired power stations (0.027 to 0.031 US$/MJ) (The World Bank, 2012b). The same source claims that the generation costs of geothermal power stations if its capacity is expanded could be around 0.019 to 0.025 US$/MJ, being as competitive as hydro energy, meaning that hydroelectricity production costs from small-scale plants would be 42% to 47% lower than electricity from fuel oil-based power plants, and electricity production costs from geothermal would be 40% lower than those from fuel oil-based power stations. Another study of electricity production costs in Guatemala for the year 2009, using site specific parameters, calculated that hydroelectricity production costs would be 40% lower than those for fuel and diesel oil power plants, while geothermal electricity costs would be 28% lower compared to electricity produced by fuel oil power stations (BCIE, 2009). However, it is important to notice that these costs depend on methodological choices and site-specific circumstances (Larsson et al., 2014). Therefore, they can only be used as rough estimates to compare different technologies and not as a policy making tool.

In the Expansion Plan, the integration of the power sector in Central America is also seen as an opportunity to reduce electricity costs. This implies the implementation of an international transmission line from Guatemala to Panama that will increase transfer capacity at all borders of the Central American countries to 300 MW (ECA, 2010). According to Meza (2014), this regional integration represents not only potential financial savings due to economies of scale, but also better infrastructure to cope with the variability of renewable sources of energy and take advantage of their complementary properties. At the time of writing (May, 2014), Guatemala is the Central American country with the highest installed power capacity and the main electricity exporter due to the surplus production from hydropower plants during the rainy season (El Economista, 2014). The country is to date able to trade electricity with the region through El Salvador and Honduras and in 2012 exported 196 GWh, an increase of 35% in comparison with the year 2010 (CNEE, 2013).

On the other hand, electricity imports from Mexico started to operate officially in 2010 (MEM, 2012). They covered 6.24% of total electricity demand in 2012 from January to April (CNEE, 2013), which is the dry season when hydropower plants cannot operate at full capacity. The costs of importing electricity from Mexico are lower than those related to oil fuel-fired power stations (MEM and CNEE, 2009). According to the Ministry of Energy, with the implementation of the Expansion Plan the country would be able not only to reduce oil fuel imports for power generation, but to reduce dependence on imported electricity (MEM and CNEE, 2009). They also claim that it would represent a reduction on CO_2 emissions, from 0.34 tCO_2 (metric tons) per capita with the current system to 0.14 tCO_2 per capita by 2028, as a consequence of overhauling existing power plants and increasing the share of renewable sources in electricity production.

By 2013, the total installed power capacity in Guatemala was 2973.7 MW. The growth rates of electricity production and demand (GWh) between years 2005 and 2012 have been 3.1% and 2.7% respectively, whereas the installed capacity (MW) has been growing at a pace of 4.5% during the same period (MEM, 2014). Although the growth of installed capacity has exceeded the peak electricity demand, it is important to note that the capacity to generate electricity depends on the capacity factor of the power stations. This is defined as the actual electricity output of an electric generator during a period of time to the maximum output if the generator would operate at full-load on a continuous basis, which is determined by the type of resource and technology (EIA, 2014).

Energy storage capacity is another factor that determines the ability of the system to steadily meet demand at peak load times. For instance, renewable sources like solar and wind are intermittent and their output cannot be forecasted accurately (Breeze, 2014). Hydroelectricity from run of river projects have usually limited or no storage capacity compared to plants with dams or reservoirs (Turkenburg et al., 2012). Another aspect that affects the availability of electricity, especially in countries like Guatemala that have a significant share of hydro sources, is the seasonal characteristic of hydropower; it makes the generation system vulnerable to droughts as it has occurred with other countries of the region (El Economista, 2014).

To achieve the expansion in generation and installed capacity, the CNEE has listed a number of power plants that were selected based on the amount of technical and financial information that they provided, allowing the simulation of the future state of the electricity generation system (MEM and CNEE, 2009). Among them are 46 hydro (3120 MW), 3 coal (900 MW), 4 natural gas (483 MW) 3 geothermal (300 MW), 3 biomass-coal power plants (300 MW) and 1 wind farm (50 MW) (MEM, 2013a). Future electricity demand was projected based on econometric models that use GDP growth and demand growth as variables (MEM and CNEE, 2009). Figures 4 and 5 show the updated projections for electricity and power demand for two cases: medium and high growth rates elaborated by the CNEE (MEM, 2013a), in which electricity and peak demand have average growth rates of 4.0% for the medium growth projection, and 4.6% for the high growth forecast.

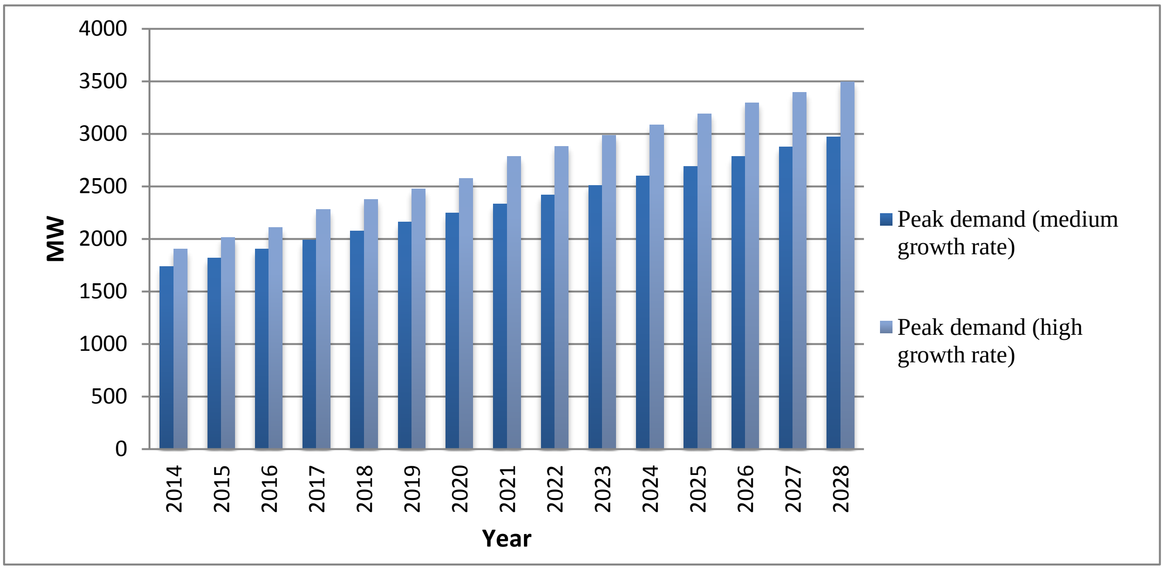


Fig. 4. Projections for growth of peak demand in Guatemala according to the Electricity Generation Expansion Plan 2014-2028
Source: (MEM, 2013a)

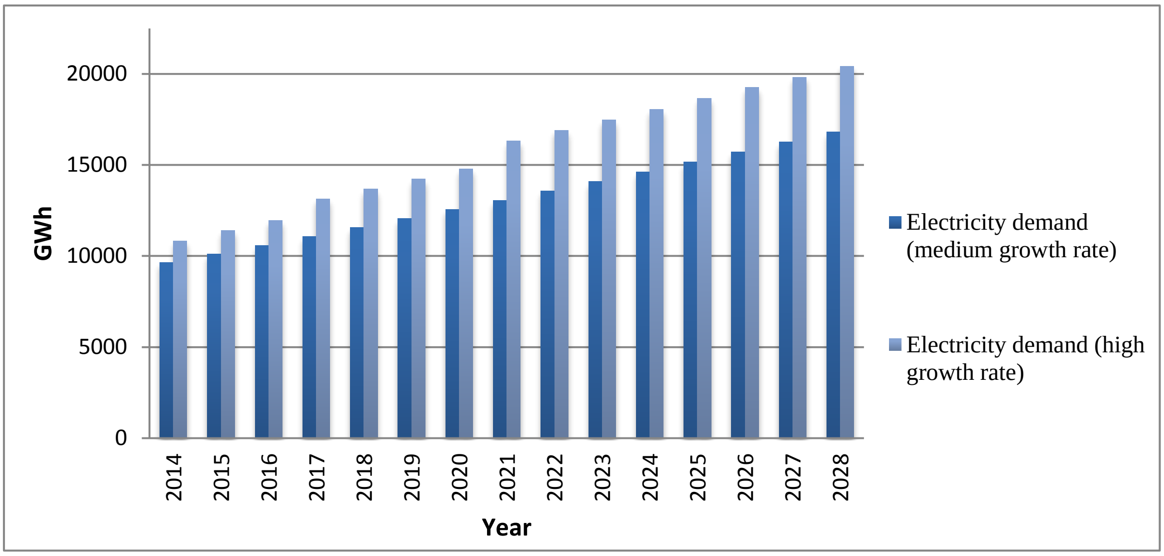


Fig. 5. Projections for growth of electricity demand in Guatemala according to the Electricity Generation Expansion Plan 2014-2028
Source: (MEM, 2013a)

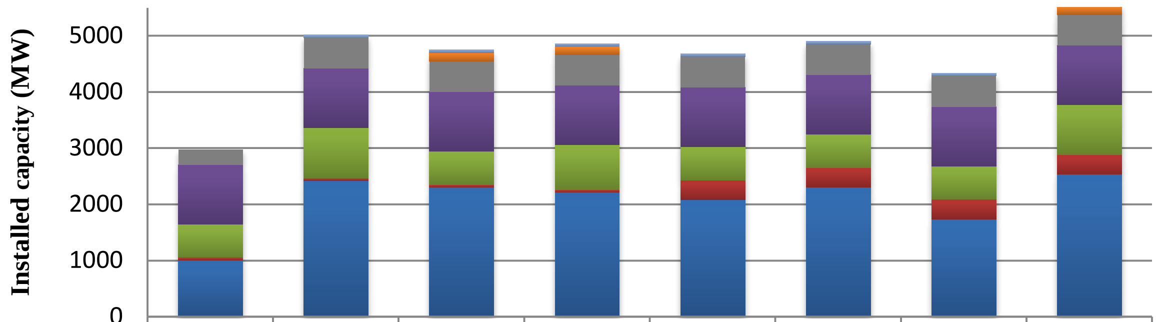
Based on these projections (Fig. 4 and 5) and different combinations of energy resources and power plants, the Expansion Plan considers seven scenarios described in Table 2. Figure 6 shows the installed capacity that would be in place by year 2028. In all the scenarios the addition of installed capacity for coal power plants is proposed to increase by the same amount.

Table 2. Scenarios proposed in the Electricity Generation Expansion Plan 2014-2028 to increase power plants' installed capacity

Scenario name	Projected peak demand	Trend of fuel prices	Electricity exports to the region	Energy efficiency-demand side	Energy sources that will contribute to increase electricity installed capacity			
					Hydro and wind	Geothermal	Biomass	Natural gas
Biomass-coal	Medium	Reference case[2]	No	No	Yes	No	Yes	No
Natural gas	Medium	Reference case	No	No	Yes	No	No	Yes
No geothermal	Medium	Reference case	No	No	Yes	No	Yes	Yes
All resources	Medium	Reference case	No	No	Yes	Yes	Yes	No
Exports	Medium	Reference case	Yes	No	Yes	Yes	Yes	Yes
Energy efficiency	Medium	Reference case	No	Yes	Yes	Yes	Yes	Yes
High demand	High[1]	High[3]	No	No	Yes	Yes	Yes	yes

[1]High demand considers industrial expansion and rural electrification projects.
[2]This is the case based on price growth projections made by the U.S. Energy Information Administration (Energy Outlook 2011) for the period 2009-2035, for natural gas (2,3%), coal (1,9%) and fuel oil (1,8%).
[3]Price growth projections for natural gas (2,3%), coal (2,2%) and fuel oil (3,2%) in case of high oil prices (Energy Outlook 2011, U.S. Energy Information Administration).
Source: MEM (2013a)

Figure 6 illustrates how the installed capacity of all the proposed scenarios will exceed peak demand projected for the year 2028, which is 2,975 and 3,497 MW for medium and high growth rates respectively. However, the final energy mix depends on the effective capacity of the power plants and the priority given to each source in each scenario. Based on the availability of resources and using cost optimization models (MEM and CNEE, 2009), the CNEE projected the energy mix of the different scenarios presented in Figure 7.



	Year 2013	Biomass-coal	Natural gas	No geothermal	All resources	Exports	Energy efficiency	High demand
wind	0	50	50	50	50	50	50	50
natural gas	0	0	150	150	0	0	0	150
coal	272	547	547	547	547	547	547	547
fuel oil	1056	1056	1056	1056	1056	1056	1056	1056
biomass	594	894	594	794	594	594	594	894
geothermal	49	49	49	49	349	349	349	349
hydro	1002	2415	2299	2210	2079	2301	1735	2528

Fig. 6. Installed capacity growth (MW) of different energy mix scenarios proposed in the Electricity Generation Expansion Plan 2014-2028 compared to the year 2013
Source: (MEM, 2013a)

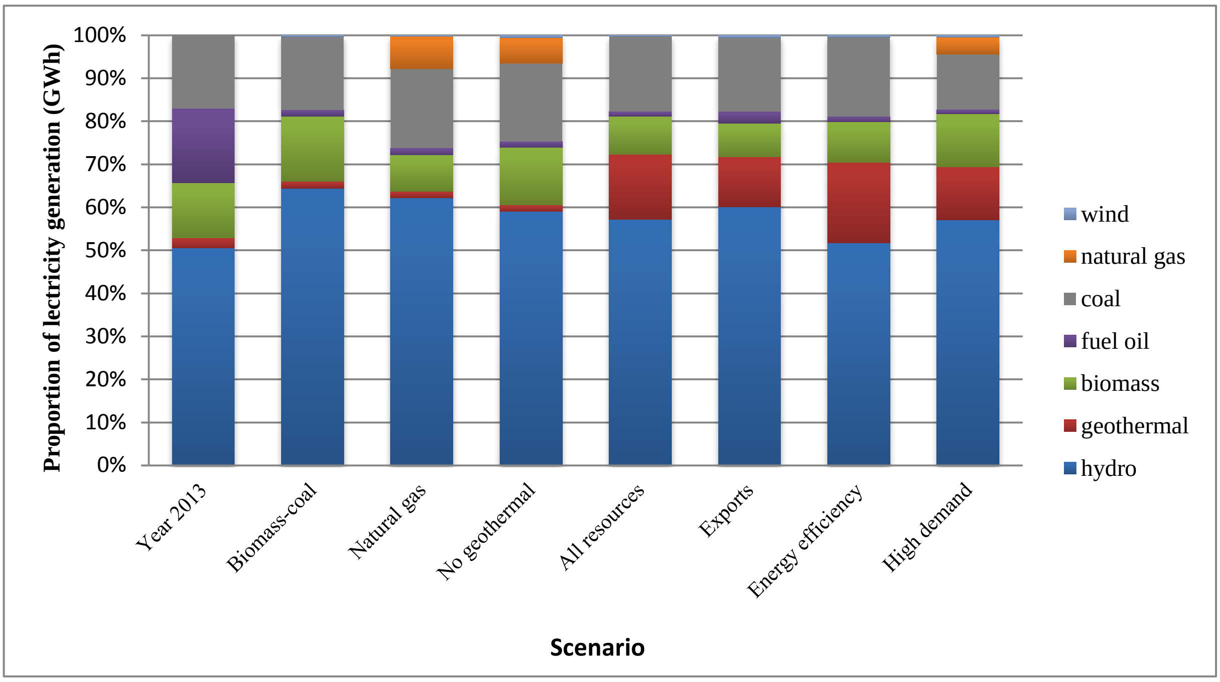


Fig. 7. Energy mix for electricity generation of the different scenarios proposed in the Electricity Generation Expansion Plan 2014-2028 compared to the year 2013
Source: (MEM, 2013a)

3. Methodology

This thesis compiles information from secondary sources about the present state of the electricity generation system in Guatemala as well as future perspectives of energy mixes delineated in the Expansion Plan. The future scenarios of energy mix proposed by the CNEE have been built up upon assumptions of increasing demand due to economic and population growth, and contemplate the addition of generating capacity through the construction of new power plants.

Because of its complexity and the different meanings that energy security can have under different circumstances (Cherp et al., 2012), the evaluation of the electricity generation system of Guatemala is conducted following an assessment framework proposed by Cherp and Jewell (2013). It aims to evaluate a specific energy system in a systematic way, and allows identification of context-sensitive vulnerabilities (Jewell, 2013). The framework has been extended in this thesis to cover concerns related to sustainable development. It starts by defining energy security for the purpose of the study in order to provide a conceptual framework that sets the basis for the rest of the assessment. The second step involves the delineation of the system under study, to understand its dynamics and characteristics that lead to identification of potential causes of disruptions and sustainability concerns. The system's vulnerabilities and sustainability concern are further expressed in quantitative indicators, which are applied to each of the scenarios of energy mix proposed in the Expansion Plan to be able to compare them on quantitative basis.

3.1. Defining energy security

Energy services are directly related to human security and as they provide essential services that support well-functioning societies, it is crucial to assess how securely they are supplied (Sovacool and Brown, 2010). Although energy security has usually been related to securing access to oil supplies and having direct control over national energy sources (Kruyt et al., 2009, Sovacool, 2010), the term has evolved and nowadays includes a range of technologies and different temporal and spatial dimensions (Valentine, 2011). At the same time, the distinctive features of energy systems contribute to the varying perspectives of energy security (Sovacool, 2010), and many authors recognize that its meaning depends on the framework or context in which it is analyzed (Kruyt et al., 2009, Sovacool, 2010, Cherp et al., 2012, Jewell, 2013).

For instance, national circumstances, geopolitics, personal and institutional perspectives tend to influence the notion of energy security (Sovacool and Brown, 2010). The temporal scale of energy security assessments poses conceptualization challenges as well (Valentine, 2010), because what represents a secure energy portfolio can differ depending on time horizons (Valentine, 2010). As a consequence of its contextual nature, energy security has no universal definition and there are no standard metrics to measure it (Jewell, 2013). According to Valentine (2010), the varying interpretations of the term have the possibility to produce different assessment approaches. Thus, a starting point to evaluate the security aspects of an energy system is to define the scope of the concept based on recognized policy concerns (Cherp and Jewell, 2011). In Guatemala's energy policy, one of the main goals is to achieve reliable electricity supply at affordable prices; mainly through investment in renewable sources, infrastructure and capacity expansion (MEM, 2013b).

For the purpose of this study, it is practical to start with a more general definition of energy security, to narrow it down later to the energy sub-system that is analyzed. Cherp et al. (2012) define it as *"protection from disruptions of nationally vital energy services".* Identifying threats and vulnerabilities of energy systems is crucial to conceptualize energy security (Sovacool, 2010, Jewell, 2013). Fuel import dependency and rising and volatile prices of oil affect especially low-income countries. Energy imports, as long as they do not come from politically close and trusted countries, make the supply system vulnerable, and are therefore a priority for policy-makers (Cherp et al., 2012). High energy prices also pose a threat to countries that need to break the poverty cycle in their societies (Sovacool and Brown, 2010). According to Cherp et al. (2012), affordability in relation to energy security deals with prices of energy that are influenced by changes within the energy systems, such as higher fuel prices due to scarcity or higher demand, and is not driven by other economic parameters like energy prices in relation to GDP or income per capita. Some authors agree that keeping energy prices artificially low can actually be in conflict with energy security criteria (Sovacool and Brown, 2010, Jewell, 2013), and therefore, the affordability aspect of energy security is often measured through the level of oil dependence or vulnerability to fuel prices (Kruyt et al., 2009, Jewell, 2013)

Electricity systems are highly vulnerable to risks of potential disruptions due to the limited energy storage capability of some sources and the necessity to constantly match supply with changing demand, especially in developing countries where insufficient capacity and rapid demand growth put pressure to expand the system (Cherp et al., 2012). Cherp et al. (2012) and Jewell (2013) propose diversification of supply sources and redundancy as criteria to respond to failures. According to Jewell (2013), diversity indices have been proposed to measure flexibility and resilience in electricity systems, since different sources are substitutable to produce electricity. Stirling (2010) has pointed out that diversification is valuable against uncertainty and ignorance of threats which, according to previous studies, are key questions for strategic security in the electricity sector (Grubb et al., 2006). Pursuing a diversified electricity generation mix can lead to innovation, and, as stressed by Stirling (2010), to environmental innovation that could lead in turn to sustainable energy transitions. This sustainability aspect has been taken into account as another aspect of energy security; Kruyt et al. (2009) relate it to acceptability of energy systems while Sovacool and Brown (2010) emphasize on reducing consumption of limited sources to satisfy resource demand of future generations.

Based on all these considerations that relate to electricity supply systems and the needs of developing and oil importing countries, the concept of energy security that best suits the purpose of this thesis is deemed to be: "*ensuring the availability of reliable and affordable energy services that are equitably shared, through decreasing dependence on imports, increasing diversity in the system, and increasing reliance on indigenous resources that are environmentally clean to support a sustainable economy able to meet current and future energy demand*". This interpretation of energy security is based on the International Energy Agency (Sovacool, 2010) and World Energy Council definitions of energy security (World Energy Council, 2013). Through this definition, the objectives and concerns expressed in the energy policy of Guatemala are reflected, in which volatility of energy carriers' prices, demand growth, and low electrification rates in rural areas are seen as challenges, while the availability of natural resources for power generation is considered as an opportunity to achieve self-sufficiency and sustainability in the electricity sector (MEM, 2013b).

In order to conduct energy security assessments using a structured framework, some authors suggest that is necessary to identify key dimensions that relate to measurable aspects of the system (Kruyt et al., 2009, Vivoda, 2010, Sovacool and Mukherjee, 2011). However, Jewell (2013) argues that attempts to classify energy security issues into disparate dimensions have failed to target real policy concerns by adding unnecessary aspects that are not clearly connected to local challenges. Recognizing that energy security is an interdisciplinary subject, Cherp and Jewell (2013) have identified three perspectives based on complementary disciplines and historic roots: *sovereignty* with roots in international relations and political science, associated with energy independence and control over the system's behavior (Cherp et al., 2012); *resilience,* that can be related to complex systems analysis and referred to as the ability to adapt to unpredictable disruptions; and *robustness* addressing predictable threats such as technical failures and based on engineering and natural science (Cherp and Jewell, 2011, Cherp and Jewell, 2013).

Regarding electricity systems, a key aspect associated with the robustness perspective is their reliability, because of their high vulnerability to short-time disruptions (Cherp and Jewell, 2011). Reliability can be divided into adequacy or the capacity of the system to cope with consumer demand, and security, which measures how the facilities respond to shocks within the system (Billinton and Allan, 1988). The latter relies on probabilistic methods based on historical failure data (Månsson et al., 2014) which are beyond the scope of this thesis. Thus, *adequacy, resilience,* and *sovereignty* are considered as essential dimensions in the evaluation of energy security of the electricity generation system.

3.2. The link between energy security and sustainable development

Sustainability studies the link between economic development, environmental quality and social equity, and the term 'sustainable development' highlights the call for decision making that is capable of satisfying economic and social needs without compromising the health of natural ecosystems (Rogers et al., 2008). It was defined in 1987 by the World Commission on Environment and Development as "*development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs*". Resembling the case of energy security, it has been argued that there is no universal approach of sustainable development, as the concept is open to interpretation and strategies proposed to achieve it will depend on the specific goals and needs of each country (Hopwood et al., 2005). In low-income countries, the socioeconomic aspect of sustainable development can be related to reduction of poverty and inequality.

Accordingly, the need to increase energy production and electrification coverage, while reducing costs and energy-related pollution at the same time, is desirable to improve the standard of living of the population (UN-Energy, 2007). The cycle of poverty is usually reinforced by high prices of electricity; poor people pay proportionally more for energy services and electricity prices have direct impact on the price of goods and services (Sovacool and Brown, 2010). Moreover, there is a strong correlation between energy intensity and economic growth (IEA and OECD, 2010, Valentine, 2010), the latter being one of the three components or approaches of sustainable development, in which income is maximized while maintaining constant or increasing stock of natural capital (Rogers et al., 2008). In this case, the link between energy security and sustainable development is clear when the expansion of energy systems to reach stability, as it is the priority for energy security (Jewell, 2013), and the need to make modern energy services more affordable to reduce extreme poverty, increase pressure on energy resources.

As energy systems become more complex, not only economic, but also social and environmental concerns are included in energy security assessments. However, more importance may be given to short and medium-term goals than long-terms considerations as in the case of sustainable development (Indriyanto et al., 2010). According to Sovacool and Brown (2010), regarding energy policy, sustainability means the reduction of emissions so they do not exceed the absorption capacity of the environment, extraction of non-renewable fuels at a rate equal to the development of renewable ones, and controlling the harvest rates of renewable sources to avoid exceeding regeneration rates. Economic and social aspects of energy security are usually taken into consideration through affordability and accessibility of services (Indriyanto et al., 2010).

Although environmental concerns are usually traded off against short-term priorities when delineating energy policies in developing countries (IEA and OECD, 2010), they have the opportunity to move directly to new technologies and institutional frameworks that allow to de-link energy intensity from economic growth, reducing environmental degradation (UN-Energy, 2007). In fact, concerns over fossil fuels scarcity, oil price volatility, and threats of climate change are changing the role that renewable resources play in energy security (Valentine, 2011, Jewell, 2013).

According to Valentine (2011), the cost advantage of fossil fuels in comparison with other sources or technologies, is now under debate. In terms of reducing dependence on imported fuels and diversifying energy carriers for electricity production, renewable energy projects have the possibility to enhance energy security while reducing environmental emissions and promoting economic development, since many renewable energy technologies can be implemented in small or medium-scale and decentralized systems (Turkenburg et al., 2012).

3.3. Delineating vital energy systems: Electricity generation system in Guatemala and its components

Energy security studies the vulnerability of vital energy systems, defined by Cherp et al. (2012) as systems *"that are necessary for the stable functioning of modern societies".* A vital energy system also implies the interaction of elements that, in case of a disruption, can be substituted for each other but not by elements outside the system (Jewell, 2013).This study focuses on the electricity sub-sector at the national level, which in general terms includes the generation, transmission, distribution, retailer, and consumer sectors (BCIE, 2009). The boundaries are drawn around the power generation system, which depends on various energy sources that feed different types of power stations. As it is currently designed, these sources are intended to complement each other. Hydropower has seasonal characteristics and, during the dry season from November to April, biomass power plants tend to supplement their low output. Fuel oil and coal-fired power stations operate according to fuel prices and demand, so they tend to cover periods of high demand when other sources are not available (CNEE, 2013). Geothermal power stations operate all year round (CNEE, 2012), but their current installed capacity is still relatively low compared to other sources, while the wind farm that will add 50 MW of installed capacity to the energy mix is expected to start operations in 2015 (El Periódico, 2014) and also has the possibility to complement hydroelectricity during the transition from dry to rainy season (Koberle, 2012). Natural gas-fired power plants are considered as part of the system in future scenarios of the Expansion Plan.

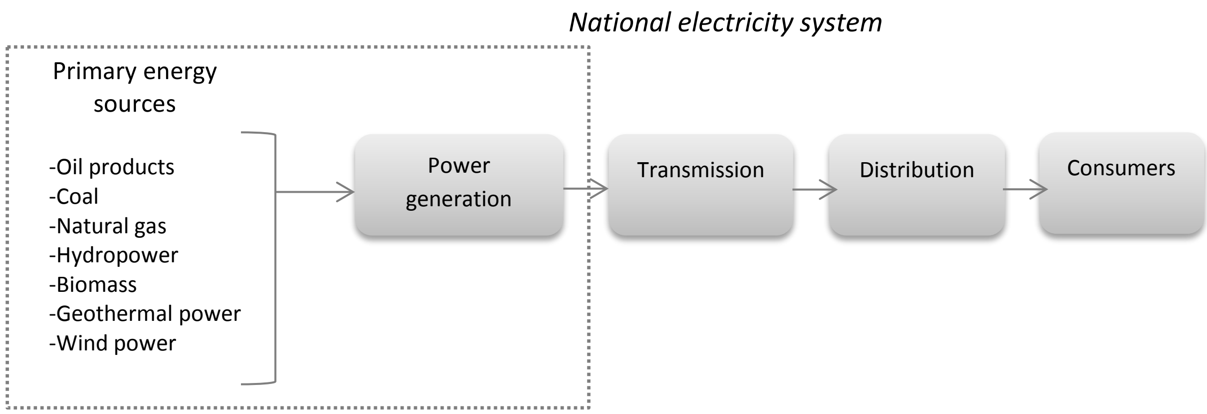


Fig. 8. Representation of boundaries (dotted line) of the electricity system under study

3.3.1. Fossil fuel power plants

Fossil fuels as energy sources have higher energy density than renewables and are relatively easy to store and distribute (Everett et al., 2012). Guatemala depends on foreign supply of fossil fuels for electricity generation, as a consequence, fossil fueled power plants using fuel and diesel oil have higher generation costs and operate only when other sources, in particular hydropower, are not able to meet the demand (Meza, 2014). The installed capacity of these power plants increased considerably in the early 1990s, but since the year 2000 it has grown at an average rate of 2.4%. Although they represent 35% (1056 MW) of the total installed capacity in the interconnected electricity system, its contribution to electricity generation in 2013 accounted for only 17% (MEM, 2014). However, during the transition from rainy to dry season, they contribute with a significant share of electricity production, increasing marginal costs of electricity (CNEE, 2013).

Coal-fired power stations' installed capacity increased significantly, by 52%, from 2010 to 2012 (CNEE, 2013). They represent 9% (272 MW) of the total installed capacity and contributed to 17% of the total electricity output in 2013 (MEM, 2014). There are six coal power plants under construction with an expected capacity of 600 to 884 MW in the coming years (América Economía, 2013). This expansion is driven by economic considerations, since fuel prices, at the time of delineating the Expansion Plan, were 0.016 US$/MJ for fuel oil, 0.004 US$/MJ for natural gas and 0.005 US$/MJ for coal (MEM, 2013a). Currently there are no natural gas-fired power stations in the country, but plans to build natural gas pipelines from Mexico to Guatemala will play an important role in investment decisions and future transformation of the electricity generation mix (Prensa Libre, 2014).Compared to oil products and coal, natural gas has lower CO_2 emissions and higher energy density than coal (Everett et al., 2012), and has the possibility to reduce electricity costs since it is expected that natural gas and coal-fired power production will phase out fuel oil-based electricity generation by 2028 (MEM, 2013a).

3.3.2. Hydropower plants

Hydropower technology is based on exploiting the kinetic energy of falling and flowing water (Rogner et al., 2012). It is considered to be the most mature and developed among the renewable options (Rogner et al., 2012). Due to their ability to store energy and provide continuous electricity supply to the system, hydropower plants with reservoirs play an important role in matching supply with demand during peak loading times (Turkenburg et al., 2012). Environmental and social impacts related to the construction of large dams and reservoirs have favored small-scale projects in the Central American region (GENI, 2012). In some cases, community-scale systems of tens of kilowatts have been built in remote areas, giving access to electricity to small villages in Guatemala (Koberle, 2012). The largest plant with a reservoir has 300 MW of installed capacity and its construction involved the relocation of indigenous communities. After this, projects requiring building of large dams have taken place under public controversy (Koberle, 2012). In the year 2013 the installed capacity of hydropower was 1,002 MW (34% of the total installed capacity), accounting for 51% of the total amount of electricity produced (CNEE, 2013).

Through most of the 20th century, hydropower has been the most important source of electricity in Guatemala, with hydroelectric plants operating for over 70 years (Koberle, 2012). During the rainy season in Guatemala, which occurs from May to October, these plants usually increase their output and in some cases have been able to supply up to 70% of electricity demand; while during the dry season, from January to April, can reduce their contribution significantly. For instance, in the year 2009, hydroelectricity represented only 24% of the total generation during the dry season (CNEE, 2012). This variability depends on the hydrologic cycle of the rivers that feed the hydropower plants, as well as on climatic and weather events (CNEE, 2013). In 2012 the outflow of many rivers decreased as a consequence of the transition of La Niña event in July, but the largest hydroelectricity dam with a reservoir of yearly regulation was able to balance the hydroelectricity supply during this year (CNEE, 2013). Some authors argue that changes in the hydrologic cycle can be intensified due to climate change, but there is the possibility that the "positive and negative impacts of climate change balance each other" if there is enough capacity in the reservoirs to cope with modifications in precipitation patterns (Turkenburg et al., 2012).

3.3.3. Electricity from biomass

The second most important source of renewable energy in Guatemala's electricity sector comes from biomass (CNEE, 2012). In this case, electricity is generated using sugar cane bagasse through thermal conversion (Meza, 2014). These power plants are owned by the sugar cane industry in Guatemala, which is a strong and well-organized sector that has been able to produce electricity independently since the 1980s (Koberle, 2012, Meza, 2014). The output is used not only for the operation of the sugar mills, but the excess is sold to the national grid and complements the low production of hydroelectricity during the dry season, which corresponds to the harvest period of sugar cane from November to April (CNEE, 2012). During the non-harvest period, most of these plants continue their operations using fuel oil (Koberle, 2012), but from 2015, fuel oil will be replaced by coal (MEM, 2013a). In 2013 their installed capacity (594 MW) represented 20% of the total installed capacity in the country, and its contribution to electricity generation was 13% (MEM, 2014).

According to the Ministry of Energy, the sector has potential to increase the generating capacity through optimization and expansion of already installed power plants (MEM, 2013a). Guatemala has the largest sugar cane mills and plantations in the Central American region (GENI, 2012), and ranks as the 8th producer of sugar cane in the world (Meza, 2014). By the year 2011, the area used in the country by sugarcane plantations was 2,230 km^2, and according to the Guatemalan Sugarcane Research Center, this area could increase to 3,500 km^2 in the near future (Cutz et al., 2013). The advantage of using sugarcane residues is the lower energy requirements of sugarcane crops in comparison with other sources of biomass, while the disadvantage is their long growing season, which allows harvesting only once a year (Cutz et al., 2013). For this reason, proposals have been made to diversify the sources of biomass to other agricultural by-products or wastes, taking advantage of the strong agro-industrial sector and the extensive amount of by-products in the form of waste (Koberle, 2012).

3.3.4. Geothermal power plants

Geothermal energy can be defined as the natural heat of the Earth stored and created in the core, mantle and crust due to the decay of radioactive isotopes, and can be used when water from deep wells is transported through pipes and recovered as hot water or steam (Rogner et al., 2012). The steam is then used to turn a turbine-generator set to produce electricity (Turkenburg et al., 2012). This type of energy can be classified as renewable as long as the energy removed from the source is replaced at a continuous rate on a time period similar to the energy removal (Turkenburg et al., 2012). Geothermal fields are usually located in active volcanic areas and close to boundaries of tectonic plates, which characterizes areas of Central America located in the Pacific Ring of Fire (The World Bank, 2012b), and specifically the south of Guatemala with a chain of 27 volcanoes (BCIE, 2009). In the year 2013, the installed capacity of geothermal power stations was 49 MW, representing 1.6% of the total installed capacity and 2% of electricity generation (MEM, 2014).

The high upfront costs and risks of exploration and drilling phases are barriers for further development of this technology (Koberle, 2012). Nevertheless, the contribution that geothermal power plants could make to the electricity generation system is important because of its base-load capability, or the ability to produce electricity at a continuous rate, offering a reliable and secure supply of electricity. Their high capacity factor is another positive aspect, achieving more than 90% in new plants (Turkenburg et al., 2012). According to different studies, the operational costs of geothermal power are similar to thermal or hydropower (GENI, 2012, Koberle, 2012, The World Bank, 2012b).

3.3.5. Wind power plants

Wind is the consequence of the warming effect of solar radiation which causes air to flow from warmer to cooler regions; these air flows can be harnessed through the movement of windmills and wind turbines to generate electricity (Everett et al., 2012). In areas with high wind speed, producing power with wind turbines is competitive in economic terms (Turkenburg et al., 2012). Unlike with other technologies, the possibility of matching supply with demand using wind power technology is constrained by the fact that it has a variable output that cannot be guaranteed or forecasted accurately (Breeze, 2014).

According to Koberle (2012), the Solar and Wind Energy Resource Assessment wind maps point out that the best places to install wind farms in Guatemala are located in the southwestern foothills, which are close to the capital city, the most populous area in the country and with the best transmission infrastructure. Another advantage of deploying wind power technology in the country is its possibility to complement hydropower during the transition from dry to rainy season, when winds are most reliable and dams' reservoirs are at their lowest levels (Koberle, 2012). However, the Expansion Plan takes into consideration the installation of only one wind farm with 50 MW of installed capacity (MEM, 2013a), representing no more than 1% of the total electricity to be produced in all the scenarios. This is because most of the Expansion Plan projects will be financed through private investment (MEM and CNEE, 2009). Therefore, there is a tendency to select the most profitable options, as is the case of hydropower projects in Guatemala. Due to the short term-high return investment and long useful life of the facilities, most of the installed power aimed at increasing the share of renewables were allocated to hydropower projects in 2012 (Gudiel, 2012), giving low priority to other technologies like wind power.

3.4. Identification of vulnerabilities and sustainability concerns

Vulnerabilities of an energy system can be related to potential risks that can cause disruptions to the system (Cherp et al., 2012). In this assessment, three dimensions of energy security have been selected to identify specific concerns of the system under study: *adequacy* as a basic aspect of reliability, *resilience,* and *sovereignty.* They are based on the characteristics of electricity generation systems and the possibility to address historical and disciplinary perspectives of energy security (Billinton and Allan, 1988, Cherp and Jewell, 2011).

Regarding sustainable development, its three components commonly referred as the "triple bottom line": economic, social, and environmental (Rogers et al., 2008) are used to define key concerns in this area. Economic optimization of electricity services has the possibility to impact both energy security and sustainable development (Valentine, 2010, IAEA, 2005), and environmental concerns are being included in energy security analyses but in some cases can be treated more as constraints than main goals for short-term assessments (Jewell, 2011). For the purpose of this study, they are categorized as dimensions of sustainable development to be able to distinguish the impacts of the electricity generation expansion on each area. Table 3 shows how each dimension is used to identify key factors that can later be translated into indicators.

Table 3. Energy security and sustainable development concerns to identify vulnerabilities of the electricity generation system of Guatemala

	Energy security dimensions			**Sustainable development dimensions**		
	Adequacy	*Resilience*	*Sovereignty*	*Economic*	*Social*	*Environmental*
Electricity generation system	Power shortages that could cause interruptions in electricity supply Power plants and infrastructure's capacity to respond to peak demand	Ability of the system to switch to different sources of energy in case of disruptions in fuel supply	Dependence on imported fuels	Inadequate electricity supply to foster economic development	Lack of equity in access to electricity	Emissions of carbon dioxide (CO_2), carbon monoxide (CO), sulfur oxides (SO_x), nitrogen oxides (NO_x) and particulate matter related to combustion of fossil fuels and other sources, as well as ecosystem disturbances due to the use of natural resources.
Energy sources:						
-Fuel oil, coal and natural gas	Availability of supply	Limited diversity of suppliers	Import dependency	Increase or volatility of prices that may impact user's ability to pay for electricity	Negative impact on population's health associated to emissions	Emissions of CO_2, CO, SO_x, NO_x, particulate matter.
-Hydropower	Seasonal water availability and storage capability	Diversity and distribution of hydro-electric dams	---	---	Possible relocation of communities	Downstream effects on ecosystems, methane emissions in large dams
-Geothermal power	---	Limited amount of power plants	---	---	---	CO_2 emissions (lower than fossil fuels), chemical pollution
-Biomass from sugar cane residues	Seasonal availability and variability	Limited diversity of sources	---	---	---	Particulate matter, sulfur dioxide (SO_2) NO_x emissions (lower than fossil fuels)
-Wind power	Intermittency and availability	Limited amount of wind farms	---	---	Possible land use conflicts	Disturbance to ecosystems depending on the location of wind farms

Sources: Cherp et al. (2012), Rogner et al. (2012), Larson et al. (2012), Turkenburg et al. (2012).

Vulnerabilities of renewable energy sources are in most cases difficult to quantify, especially their availability, due to the high variability of energy sources (Jewell, 2011). In terms of sovereignty, hydroelectricity presents risks when the plants are located on transboundary water resources (Cherp et al., 2012), which is not the case of any of the hydropower plants considered in the Expansion Plan (MEM, 2013a). The rest of the renewable sources do not depend on imported fuels to generate electricity, and therefore do not render sovereignty concerns. Taking the electricity generation system as a whole, the utilization of renewable sources is favorable in terms of resilience, making the system more diverse (Cherp et al., 2012).

The economic dimension of sustainable development is concerned with rising levels of economic welfare and protecting economic growth from external negative impacts (Rogers et al., 2008). In this sense, the main threat identified in Table 3 is the high and volatile price of oil products, which tends to increase electricity prices when a significant proportion of electricity that feeds the interconnected power system comes from fuel oil-fired power plants (CNEE, 2013). Decreasing electricity affordability affects indirectly the prospects of economic development, limiting access to poorer households and increasing the subsidy burden that has proven to be economically unsustainable (Santizo, 2011).

3.5. Selecting energy security and sustainable development indicators

Indicators selected in this phase reflect vulnerabilities identified in the previous section. However, it is important to remark that there are no standard indicators to measure energy security (Sovacool and Mukherjee, 2011), and that they represent only a quantitative proxy of the system's capacity and risks (Cherp and Jewell, 2013). In Table 4 the set of indicators used to assess the electricity generation system in terms of energy security and sustainable development are provided.

Table 4. Energy security and sustainable development indicators

Dimension	Indicator	Components
Adequacy	Spare capacity of electricity generation	Installed capacity divided by the critical or average load[1]
Resilience	Diversity of electricity generation sources	The Shannon-Weiner index measures the degree of variety and balance of electricity generation by energy source, and the Herfindahl-Hirschman index measures diversity as the share of each type of electricity generation source in relation to the total electricity production [2]
Sovereignty	Import dependence	Electricity produced from fuel oil, coal, and gas-fired power plants in relation to total electricity generation[3]
Economic	Reliance on oil products for electricity production	Electricity produced from fuel oil-fired power plants in relation to total electricity generation
Social	Electricity coverage	Share of population with access to electricity[4]
Environmental	Renewable energy share in electricity production	Electricity produced from renewable sources of energy in relation to total electricity production

Sources: [1]Jewell (2013), [2]Grubb et al. (2006), Hickey et al. (2010), [3]Cherp et al. (2012), [4]IAEA (2005).

In this study, the **spare capacity of the electricity generation system** has been chosen to assess the ability of the system to cope with peak demand without interrupting the supply. This is an aspect of the static conditions of a power system and does not take into account system disturbances, but considers capacity requirements to be able to satisfy consumer demand within predictable operational constraints (Billinton and Allan, 1988). For this case, values above 1 mean that there is surplus capacity in the system. Since the available power depends on the capacity factor of each type of power plant (Koberle, 2012), the installed capacity of each source (Fig. 6) has been adjusted to its effective capacity (or technically available capacity): 80% for fossil fueled thermal power (BCIE, 2009), 54% for hydro (CNEE, 2012), 85% for geothermal, 45% for biomass, and 25% for wind power (Koberle, 2012) and divided by the projected peak demand for year 2028 (Fig. 4).

According to Cherp et al. (2012), the main resilience metric used in energy supply assessments is the **diversity of primary energy sources**. Diversification of sources is particularly relevant to enhance resilience as it provides a "robust response to the most intractable forms of uncertainty, ambiguity and ignorance" of possible threats (Stirling, 2010). It has also an impact on reliability, as the availability of alternative options decreases the probability of supply interruptions (Hickey et al., 2010). To measure diversity, two indices are applied:

- Shannon-Weiner (S-WI) index = $-\sum_i p_i \ln(p_i)$, where p_i is the proportion of electricity generation represented by the ith type of generation classified by energy source (Fig. 7). The equation is based on mathematical ecology and takes into consideration aspects of variety and balance because diversification increases as the proportion of each fuel or energy source is more evenly distributed (Hickey et al., 2010). The index value increases for systems with a greater amount of independent sources (Grubb et al., 2006).

- Herfindahl-Hirschman (HHI) index = $\sum_i p_i^2$, where p_i is the proportion of generation represented by the ith type of generation classified by energy source (Fig. 7) and expressed as a percentage (Grubb et al., 2006). It is based on economics and measures market concentration, where lower index values mean less market power and greater diversity (Hickey et al., 2010). This index decreases as the number of firms or, in this case, generation sources increase in number and the disparity in the size of those sources decreases (Roques, 2008). That is, the higher the value, the less diversified is the system.

Sovereignty, as previously explained, implies control over local energy sources. According to Cherp et al. (2012), import dependency of fuels is the main sovereignty concern at the national level, and presumably the most commonly used indicator to measure energy security. **Reliance on imported fuels** can be associated with both physical and price disruptions (Jewell, 2013).

Since electricity services are only a mean and not an end to foster economic development (IAEA, 2005), how they support economic development can only be measured indirectly through factors that have an impact on affordability of electricity. A metric that is associated with price volatility is oil dependency in the end use sector (Kruyt et al., 2009). Thus, the **share of oil products in electricity production** is an indicator of how exposed the system is to unstable and rising fuel prices. As asserted by Roques (2008), high and volatile oil prices hamper economic growth by raising inflation and creating uncertainty that may have a negative impact on investment activities.

The social dimension of sustainable development in relation to energy services addresses equity issues, or "the degree of inclusiveness with which energy resources are distributed" (IAEA, 2005). In this regard, accessibility of electricity is measured as the **share of population with access to electricity**, and how the electricity generation expansion plan can influence it.

Environmental impacts of the electricity generation system and energy sources are listed in Table 3. Although the use of renewable sources of energy implicates environmental and social concerns as well, their potential to mitigate greenhouse gas emissions and reduce conflicts in the mining and exploitation of limited fossil fuels is recognized (Turkenburg et al., 2012). Consequently, the **renewable energy share** in electricity production is taken as indicator to evaluate if there is a transition towards environmental sustainability through the modification of energy mix.

4. Results

4.1. Spare capacity, diversity and import dependence

The results of applying the spare capacity indicator to each of the energy mix scenarios are displayed in Figure 9. It shows that the values for all the scenarios except for 'energy efficiency' are above 1, which means that there is still electricity capacity margin in all of them, although less than in the current system. The 'biomass-coal' and 'exports' scenarios have the highest values: 1.10 and 1.09 respectively, followed by 'no geothermal': 1.08, 'high demand': 1.06, 'all resources': 1.05, and 'natural gas': 1.05. It means that the best case regarding its spare capacity is the 'biomass-coal' scenario, and the worst case is the 'energy efficiency' option.

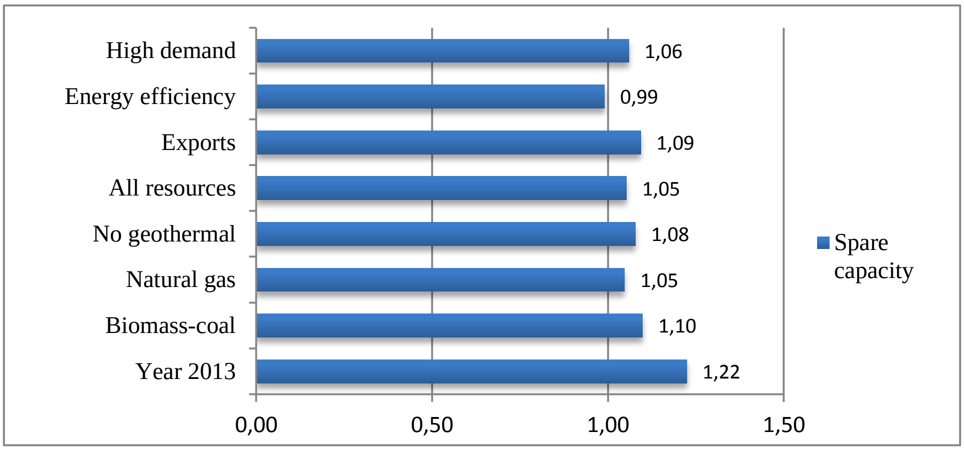


Fig. 9. Spare capacity of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

The Shannon-Weiner diversity index values of each of the energy mix scenarios for electricity production are shown in Figure 10. For all the scenarios, except 'high demand', the S-WI index value decreases in comparison to the energy mix of 2013. This means that all the scenarios are less diversified, mainly because changes in the share of generation corresponding to hydro sources in most of them make the system less balanced, although the number of sources increases in all of them. The highest value corresponds to the 'high demand' scenario: 1.3, followed by 'energy efficiency': 1.27, 'no geothermal': 1.21, 'exports': 1.19, 'all resources': 1.19, 'natural gas': 1.16, and 'biomass-coal': 1.02. Thus, the best case in terms of diversity using the S-W index is the 'high demand' scenario, and the worst case is the 'biomass-coal' scenario.

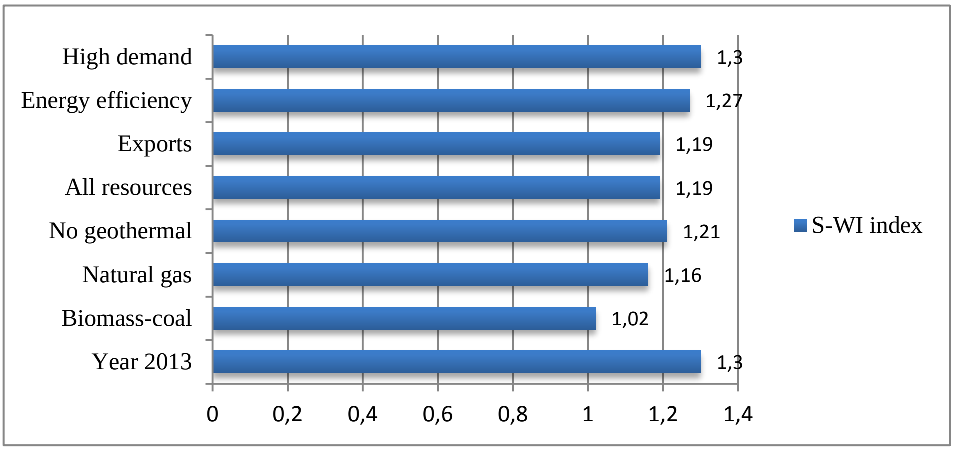


Fig. 10. Shannon-Weiner index values of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

Figure 11 displays the values of the Herfindahl-Hirschman diversity index of each of the scenarios. The lowest value corresponds to the energy mix of 2013, followed by the scenarios 'energy efficiency': 3,454, 'high demand': 3,735, 'all resources': 3,879, 'no geothermal': 4,027, 'exports': 4,107, 'natural gas': 4,331, and 'biomass-coal': 4,672. In terms of disparity in the share of energy sources, the 2013 energy mix is again more diversified. Among all the scenarios, the 'energy efficiency' case is more diversified when using the HHI index, while the 'biomass-coal' scenario is the least diversified.

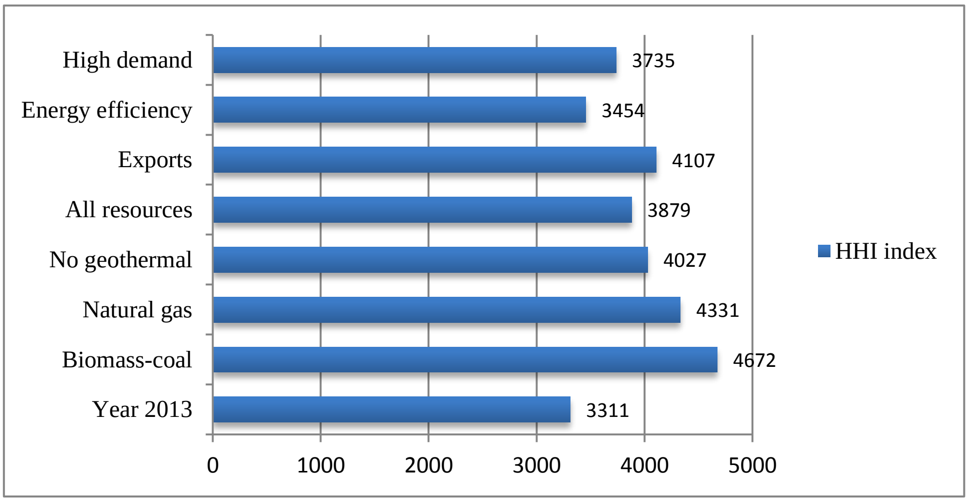


Fig. 11. Herfindahl-Hirschman index values of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

The import dependence values of the energy mix scenarios are illustrated in Figure 12 as the proportion of electricity generated from fuel oil, natural gas and coal-fired power plants. Despite the addition of natural gas-fueled power plants in the system, the proportion of electricity production that relies on imported fuels is reduced for all the scenarios by at least 6% when compared to the situation in the year 2013. The scenario with the lowest dependence on foreign fuels is 'high demand': 17.9%, followed by 'biomass-coal': 18.6%, 'all resources': 18.6%, 'energy efficiency': 19.7%, 'exports': 19.9%, 'no geothermal': 25.5%, and 'natural gas': 28.0%. Therefore, the best case regarding reduction in use of imported fuels is the 'high demand' scenario, in which import dependence would be reduced by 16.5% in comparison with the year 2013, and the worst case would be the 'natural gas' scenario with a reduction of 6.4% of imported fuels compared to the year 2013.

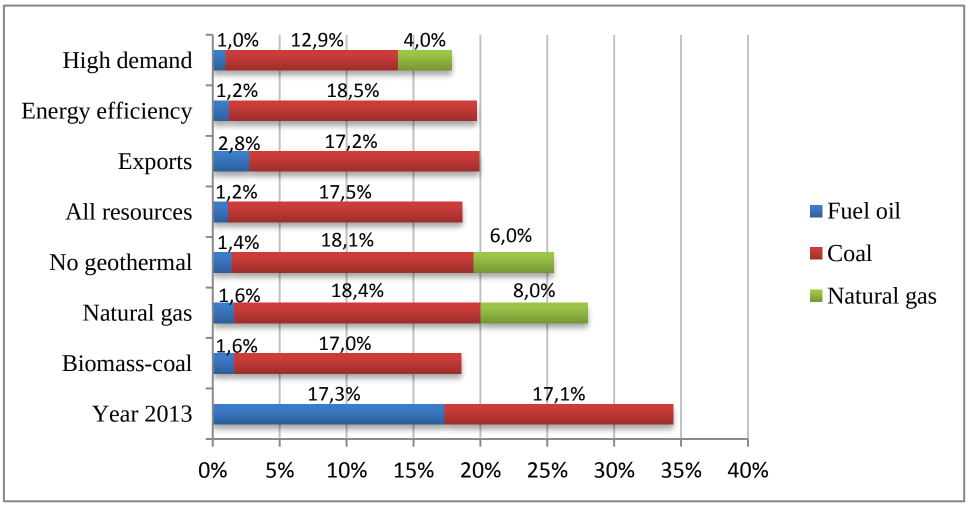


Fig. 12. Import dependence of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

4.2. Economic, social and environmental concerns indicators

The reliance on oil products of the energy mix scenarios as an indicator of their economic impact is shown in Figure 13. It can be observed how the proportion of electricity produced by fuel-oil based power plants is considerably reduced in all the proposed scenarios by at least 14%. The scenario with the lowest dependence on oil products is 'high demand': 1.0%, followed by 'energy efficiency': 1.2%, 'all resources': 1.2%, 'no geothermal': 1.4%, 'natural gas': 1.6%, 'biomass-coal': 1.6%, and 'exports': 2.8%. The best case in this aspect would be the 'high demand' scenario with a reduction in oil products dependence of 16.3% when compared to the year 2013, while the worst case would be the 'exports' scenario with a reduction in oil products dependence of 14.5% compared to the year 2013.

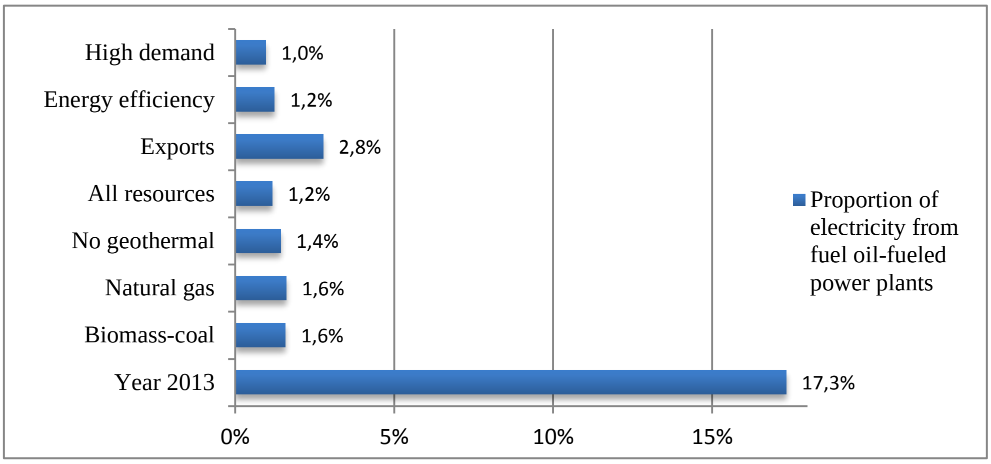


Fig. 13. Reliance on oil products for electricity production of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

The social aspect of equity in electricity access is measured through the share of population with access to electricity, which is projected to increase from 85.6% as estimated in year 2012, to 95% by 2027 if all the scenarios based on 'medium' growth projections take place. Only the 'high growth' scenario takes into consideration rural electrification and large industrial projects that require greater capacity expansion, having the possibility to increase the proportion of population with access to electricity at higher rates than the rest of scenarios.

The share of renewable energy in the energy mix is considered as an indicator of the environmental impact of energy mixes. Figure 14 shows how this proportion increases in relation to the 2013 energy mix by at least 7%. The highest share of renewable energy for electricity generation corresponds to the 'high demand' scenario: 82.2%, followed by 'all resources': 81.4%, 'biomass-coal': 81.4%, 'energy efficiency': 80.3%, 'exports': 80.1%, 'no geothermal': 74.5%, and 'natural gas': 72.4%. Thus, the best case in terms of increasing the share of renewable sources would be the 'high demand' scenario with an increase of 16.6% in comparison with the year 2013. The worst case would be the 'natural gas' scenario, in which the share of renewable sources for electricity generation would increase by 6.8% when compared to the year 2013.

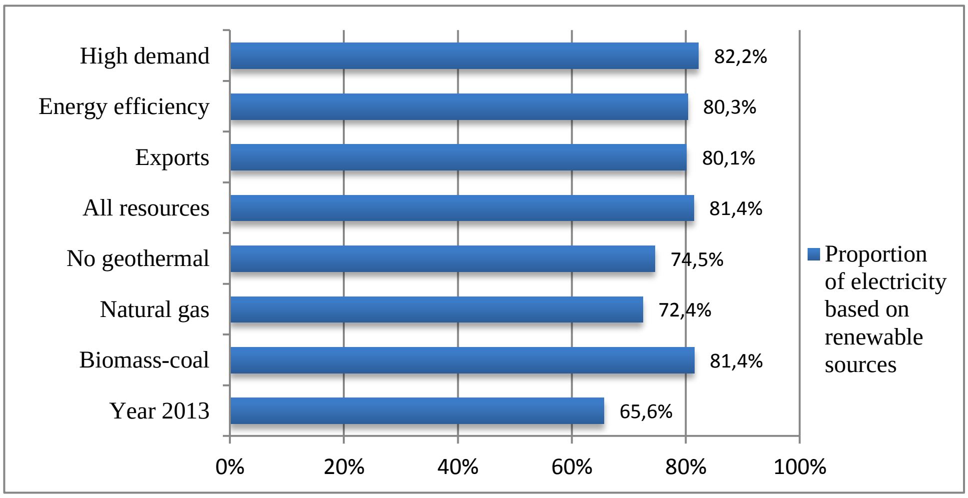


Fig. 14. Renewable energy share of each of the energy mix scenarios of the Electricity Generation Expansion Plan 2014-2028

5. Discussion

5.1. Spare capacity of the electricity generation system as an aspect of adequacy

In general terms, the spare capacity indicator reveals that the surplus capacity of the system in all the scenarios is comparable to each other, since it has been adjusted to balance the projected demand. The fact that it decreases in comparison to the year 2013 is due to the possible overestimation of demand projection. For instance, peak demand between 2005 and 2013 has grown at an average pace of 2.5% (CEPAL, 2013), whereas the projections of the Expansion Plan are 4.0% and 4.6% for the 'medium' and 'high' demand growth scenarios respectively. In fact, based on these projections, the demand in 2014 would be 11% higher for the 'medium' growth and 22% for the 'high growth' cases than those registered for 2013. Specifically in the 'energy efficiency' scenario with the lowest spare capacity, the projected demand as forecasted by the CNEE was not adjusted to take into account efficiency measures on the demand side. This is a shortcoming of the demand forecasting, but taking into consideration the historical growth in peak demand, it is expected that the effective installed capacity in all the scenarios will maintain a capacity margin enough to meet the future peak demand.

It is also important to consider the characteristics of different power stations when evaluating the adequacy of the system to balance supply and demand. For instance, power plants fuelled by oil products, coal and natural gas can be run continuously limited only by the physical availability of fuels. Gas-turbine stations can start operations in a matter of minutes and are best suited to be used for peak times (Everett et al., 2012). Hydropower plants can also adapt quickly to peak loading, as long as they are able to store energy (Turkenburg et al., 2012), as is the case for plants with dams. The size of dams is also an important aspect, because of seasonal variations in water availability. Seasonal availability affects also the output of thermal power plants using biomass, while wind power stations cannot store energy and have an intermittent output as the wind is not available at all times (Breeze, 2014). Geothermal stations, on the other hand, can operate continuously and are not determined by weather conditions.

All of these factors are crucial in determining the best energy mix in terms of energy security. However, information that can be translated into quantitative indicators is not available, since for instance, hydropower plants in the Expansion Plan are not classified according to their type and reservoir size. But the relatively high proportion of hydroelectricity may compromise the ability of the system to meet the demand if it is not managed appropriately to address changes in water availability. Sugarcane bagasse used as fuel in biomass power plants is available during the dry season, therefore their capacity expansion considered in the ‘biomass-coal’, ‘no geothermal’ and ‘high demand’ can be considered as a favorable aspect to complement hydroelectricity when rainfall decreases. The low proportion of intermittent sources like wind power does not exceed 1% of the total electricity production in any of the energy mix scenarios, and therefore is not considered to affect the adequacy of the system in a negative way. The expansion of geothermal power capacity in the scenarios named as ‘all resources’ ‘exports’, ‘energy efficiency’ and ‘high demand’ may increase the capability of the system to meet changes in demand and provide reliable electricity.

5.2. Resilience through diversification of energy sources

A diversified energy mix for electricity generation increases the system’s resilience, since fuel supply disruptions can be effectively managed by recurring to other available energy sources. According to S-WI and HHI indices values, none of the proposed scenarios is more diversified than the energy mix of 2013, even though all of them have at least one additional energy source. The reason is that all the scenarios with the exception of the ‘efficiency’ case, increase in a higher proportion the contribution of hydroelectricity in comparison with the rest of the generation sources, decreasing the balance in the system. Among all the options to modify the energy mix, the most diversified based on the S-WI index is the ‘high demand’ followed by the ‘efficiency’ option. The results of the HHI index are consistent with the S-WI index. They show that the 2013 energy mix has more balance in the share of generation sources, followed by the ‘energy efficiency’ and ‘high demand’ scenarios.

Nevertheless, it is worth noting that diversity indices used in this assessment do not reflect the dynamics of the system. Neither do they measure the level of disparity in order to be able to cope with unexpected or sudden disruptions. For instance, the addition of at least one energy source in all the scenarios in comparison with the 2013 energy mix may add flexibility to the system. On the other hand, the fact that the dominant source of electricity is hydropower in all the scenarios raises the same concerns as in the spare capacity evaluation. The amount of hydropower stations to be constructed if any of the scenarios take place would be between 53 and 58 located in different parts of the country. From the resilience perspective, this could improve the system’s ability to cope with power plants’ failures, because the generating capacity would not be concentrated in few and large facilities.

5.3. Import dependence to address sovereignty concerns

In comparison to the energy mix of 2013, all the scenarios reduce the proportion of electricity produced from imported fuels. Reliance on oil products for electricity generation decreases considerably in all of them. ‘Natural gas’ and ‘no geothermal’ scenarios show the highest dependence on imported fuels among all of the future options. The sovereignty dimension addresses issues related to international relations and control over energy systems to prevent price manipulation and disruptive actions (Cherp and Jewell, 2013). Therefore, decreased dependence on foreign oil products would enhance energy security since their production is concentrated in few countries (Cherp et al., 2012). Reliance on coal is relatively the same for all the scenarios, decreasing slightly in the ‘high demand’ case. In comparison to oil and natural gas, coal reserves are more geographically dispersed and not controlled by regional markets (Cherp et al., 2012). Natural gas supply is contemplated in the ‘natural gas’, ‘no geothermal’ and ‘high demand’ scenarios. Since it would have only one supply route, dependence on this source would be considered a threat to energy security if it contributed with a higher share of electricity supply.

5.4. Economic impact

When evaluating the possible economic impact of changes in the generation matrix, the results show that all the scenarios contribute to decrease reliance on oil products, from 17.3% in the 2013 energy mix to 2.8% in the worst case (‘exports’ scenario). This aspect is important to both energy security and economic development, since the use of oil products, specifically oil fuel in thermal power plants, has contributed to increase the spot price of electricity in recent years (CNEE, 2012). In a developing country like Guatemala with a high proportion of its population living in poverty, high electricity prices limit the ability of users to pay for the service. Electricity subsidies in the country have proven to be economically unsustainable, because of the variable and rising prices of oil products (Santizo, 2011). They have also limited the budget to upgrade the state-owned power facilities, like the largest hydropower station (300 MW) that is able to supply electricity all year round due to their reservoir size (CNEE, 2012). Therefore, the benefits of decreasing electricity prices can be translated into opportunities to invest on infrastructure, providing in this way better electricity services that support industrial activities for economic development.

5.5. Social impact

Electricity is a means to provide basic services that can improve the well-being of societies. Access to electricity is expected to increase in Guatemala if the generation and transmission capacity of the electricity sector is upgraded. All the scenarios would contribute to achieve the energy policy goal of increasing electricity access, basically by increasing its affordability and expanding the interconnected system capacity (MEM and CNEE, 2009). However, only the 'high demand' scenario would have enough capacity to support electrification in remote rural areas, having the possibility to provide universal access by 2028. Although this can improve the living conditions of the poor, poverty alleviation as a sustainable development goal would require other actions and policies. For instance, the provision of complementary infrastructure for better sanitation and health services, and the development of income generating activities to raise living standards. Another factor to consider under this dimension is that expansion of generation from renewable sources can play an important role in job creation in rural areas.

The social impacts of renewable energy technologies will depend on resource management practices and the scale and location of the projects, particularly in the case of hydropower. As it constitutes the main renewable source in all the scenarios, the scale of the projects could affect not only delicate ecosystems but also nearby communities if mitigation measures are not followed. Almost half of the total amount of new hydro plants considered in the Expansion Plan will be located in the Guatemalan highlands (MEM, 2013a), a region with the largest proportion of indigenous population. This part of the population is particularly vulnerable, since among indigenous communities the poverty rate is 75%, and the level of extreme poverty is higher than for the rest of the population: in 2011 was 22% compared to 7.6% for non-indigenous people (The World Bank, 2012a). One aspect that has been suggested by Sovacool and Mukherjee (2011) when evaluating energy security through a more integrated framework, is having "stable, transparent, and participatory modes of energy policymaking". In Guatemala, the high levels of corruption, as measured by the Corruption Perception Index 2013 (Transparency International, 2014), may hinder the achievement of socioeconomic development goals, and create disincentives for transparent planning and accountability. Because all of the scenarios would be implemented under the same political and institutional framework, this study does not take into account any indicator related to this aspect as it would not be useful for comparison purposes. However, it is an important aspect to consider when evaluating the possible socioeconomic and environmental impacts of the Expansion Plan. Therefore, if social and environmental impact assessments are not carried out in a transparent way, the expansion of the electricity generation system in the country could cause social conflicts and affect the livelihood of vulnerable groups that live nearby the location of new power plants.

5.6. Environmental impact

As an indicator of environmental sustainability, an increase in the share of renewable energy for electricity generation in comparison to year 2013 occurs in all the scenarios. The energy mix with the highest share of renewable sources is the 'high demand' and the lowest share is in the 'natural gas' option. This metric alone is not sufficient to measure the environmental impact of changes in the energy mix, since deployment of renewable energy technologies raises environmental concerns as well. Nevertheless, increasing renewables share offers opportunities to reduce greenhouse gas emissions and pollution related to fossil fuels combustion (Turkenburg et al., 2012). However, the interest in increasing the capacity of coal-fired power stations may outbalance this benefit as energy intensity for electricity generation increases. Among the fossil fuels, coal has the highest emission factor for greenhouse gases (Cherp et al., 2012), and contributes to local pollution with negative consequences for human health and ecosystems.

5.7. Comparison of energy mix scenarios

The **'biomass-coal'** option prioritizes the capacity expansion of biomass power plants. It is intended to balance the output of hydropower plants during the dry season. This scenario has the highest proportion of hydroelectricity generation, and consequently the lowest values for diversity indices. Since it does not include natural-gas fired plants, its dependence on imported fuels is among the lowest.

The **'natural gas'** scenario is also highly dependent on hydroelectricity and has the highest proportion of electricity from natural gas and from imported fuels among all the scenarios. Although natural gas reserves at a global scale are larger than oil reserves, this is a limited source of energy that could increase risks of disruptions due to the low diversity of import sources and supply routes (Cherp et al., 2012).

'No geothermal' scenario is a combination of conditions from the 'biomass-coal' and 'natural gas' cases, relying on biomass and natural gas sources to complement hydroelectricity production during the dry season. Accordingly, this energy mix does not depend on hydroelectricity as heavily as the previous two scenarios, and the values obtained from the S-WI and HHI indices show that it is more diversified as well. However, it has the second highest proportion of electricity from imported fuels, after the 'natural gas' scenario.

The **'all resources', 'exports',** and **'energy efficiency'** options present more similarities among them. In the first place, all of them consider the expansion of geothermal power capacity, without increasing production from biomass sources and without taking into account generation from natural gas. The main difference is that the installed capacity is greater in the 'exports' case, in which national demand could be supplied using renewable sources while coal power plants would be used to export energy to neighboring countries (MEM, 2013a), taking advantage of the regional power sector integration. This could represent economic opportunities for the country and contribute to support economic growth, as long as the revenues foster local income generation. The 'energy efficiency' scenario, on the other hand, has the lowest total installed capacity and the lowest share of hydroelectricity production, assuming that efficiency measures on the demand side would be implemented by then. This energy mix is also the second most diversified after the 'high demand' scenario, and with the lowest level of supply concentration in accordance with the HHI index.

The **'high demand'** scenario is the only one that considers rural electrification and large industrial projects. The proportion of hydroelectricity in this energy mix is the second lowest among all of the scenarios. It involves an increase in the share of geothermal electricity and is the most diversified according to its S-WI index value. Although it would incorporate the natural gas-fired station, its reliance on imported fuels is in proportion one of the lowest.

5.8. Limitations

The limited availability of data regarding electricity production and consumption in the country has constrained the number and choice of metrics to evaluate electricity generation system from energy security and sustainable development angles. Due to the complexity of power generation systems, the indicators selected in this thesis are not able to cover all the aspects that may influence the security of electricity supply and sustainability patterns. They can only be used as a tool to compare different options and identify changes using concise information about the static properties of the system. Thus, the results of the energy security indicators can only be interpreted under the assumptions of infrastructure improvements suggested in the Expansion Plan, and the outcomes pertaining sustainable development, under the assumptions of transparency and well-planned mitigation measures during the installation and operation of power plants. More detailed information about the type, storage capability and specific location of hydropower stations, as well as economic and reliability aspects of the electricity infrastructure would have allowed a more complete analysis without relying in some cases on general assumptions.

6. Conclusion

The modifications to the energy mix proposed in the Electricity Generation Expansion Plan 2014-2028 would expose the electricity system of Guatemala to vulnerabilities associated with increased reliance on hydroelectricity in most of the scenarios proposed. If these vulnerabilities are not appropriately addressed, they could limit the ability of the system to cope with the projected demand. The level of diversification of energy sources would decrease as a consequence of increasing disproportionately the share of hydroelectricity, providing an unbalanced system. On the other hand, by switching to indigenous renewable energy sources, all of the energy mix scenarios would allow more control over the system and decrease dependence on imported fuels for power generation, enhancing energy security in this aspect.

Taking into consideration the economic, social and environmental dimensions of sustainable development, the displacement of oil products for electricity generation by less volatile and more economic fuels and energy sources, can decrease electricity costs. This aspect, in combination with increased electricity access that would be facilitated through the system expansion, has the possibility of supporting economic and social development. Increasing the share of renewables can promote the transition towards a less carbon intensive electricity system. Additionally, demand-side efficiency measures can reduce pressure on natural resources. However, the capacity expansion of coal-fired power plants remains a concern regarding environmental impacts of the future energy mix for electricity generation in Guatemala.

In conclusion, energy security in the electricity sector could increase as a consequence of the capacity expansion and transformation of the energy mix to rely more on indigenous sources, taking into consideration scenarios with a more diversified portfolio that include the expansion of biomass and geothermal capacity to compensate for the vulnerability of hydroelectricity to weather events. The prospects for sustainable development in the country can be supported by the provision of secure electricity supply that takes into account efficiency and mitigation measures in the exploitation of natural resources, as well as social impact assessments to ensure that the plan will not affect the livelihood of vulnerable groups and has the possibility to contribute to increase equity in electricity access.

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