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Assessing Wave Power for Sustainable Development in Costa Rica:
Potential Role within Energy Mix and Comparative Analysis
of National Energy Sources through Triple I Index

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ASSESSING WAVE POWER FOR SUSTAINABLE DEVELOPMENT IN COSTA RICA:
POTENTIAL ROLE WITHIN ENERGY MIX AND COMPARATIVE ANALYSIS OF
NATIONAL ENERGY SOURCES THROUGH TRIPLE I INDEX

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ABSTRACT

Demand for energy and associated services, to meet social and economic development and improve human welfare and health is increasing. All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes. Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO₂) emissions. (IPCC, 2012).

Furthermore, to achieve true sustainable development energy should be acquired from renewable, low carbon, constant resources that provide stability to the grid and increase resilience to climate change, as stated by The United Nations General Assembly when calling upon member states to “galvanize efforts to make universal access to sustainable modern energy services a priority”. Stressing particularly on the importance of improving access to “reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources for sustainable development” (United Nations, 2014), thus promoting reduction of poverty, improved health conditions and mobilizing societies towards development. Costa Rica, a small Central American nation has consequently proposed attainment of Sustainable Energy for All (SE4ALL) as well as unilaterally established a Carbon Neutrality goal for the year 2021. For the nation to reach these goals becomes of great global significance as it would provide a beacon to the world that proves it is possible, while reducing learning curves for other developing nations.

Costa Rica has successfully achieved 98.95% generation of electricity from renewables for the year 2015 and access to 99.28% of the population (IDB, 2016 and Isola Wiesner, 2015). These astonishing results have not been easily attainable for the nation, and ensuring 100% access with 100% renewable sources becomes more and more difficult with a growing population, growing demand and a strong dependence on hydroelectric systems for energy generation in times of extreme climatologic variations.

This study evaluated the possibilities of diversifying the energy mix with carbon neutral energy systems to attain said goals. Additionally, it evaluated the possibility of introducing ocean energy produced by waves, as a means to achieve this. Ocean Energy has been proposed as one of the potential solutions to be considered both globally and locally; however, significant research on the topic determining its technical, economic, environmental and social viability must be

developed. Most research and development relating to ocean energies has been conducted in developed countries of the northern hemisphere. Biological and climatological conditions, as well as social and economic characteristics outside of the tropical belt are significantly different than those of the territories inside; adaptation of ocean energy technology studies to the developing and tropical context is of utmost importance.

The study pays special attention to public acceptance considered one of the most relevant issues and barriers for evaluating the sustainability of anthropogenic systems. “The development of energy systems in the future will depend on the balance of environmental impact, economic feasibility, and public acceptance.” (Takahashi & Sato, 2015) In addition, the study determines the effects of public preference in terms of acceptance or aversions to specific impacts as to define the Marginal Willingness to Pay of population, and evaluate the impact on project viability it could have.

Results identified economic barriers in the pricing of electricity that limit diversification of the energy mix. Additionally, the prohibitive nature of costs of ocean energy systems is further confirmed, and market conditions are determined for viability of wave energy to be achieved. Potential gaps in policy are defined for the regulation of ocean energy.

The study elucidates public preference of energy sources and potential market niches. Further studies to adequately price electricity without significantly affecting the industrial sector are recommended. Finally, potentially viable energy sources, such as wind and biomass, for an improved energy mix, attainment of Carbon Neutrality, and SE4ALL are determined.

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DEDICATION

In loving memory of Felipe.

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LIST OF TERMINOLOGY: ABBREVIATIONS

CABEI	Central American Bank of Economic Integration
CB	Cost Benefit Analysis
CO ₂	Carbon Dioxide
CO _{2eq}	Carbon Equivalent emissions
EF	Ecological Footprint
EJ/yr	Exajoule year
GHG	Greenhouse gases
GW	Gigawatt
ha	Hectare
ICE	Costa Rican Institute of Electricity
IDB	InterAmerican Development Bank
III	Triple I Index
IMN	National Meteorological Institute
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
kW	Kilowatt
MINAE	Ministry of Environment and Energy (Sometimes referred to as MINAET or MINAEM as important changes in internal structure where undergone to exclude telecommunications and include oceans sector)
MW	Megawatt
MWTP	Marginal Willingness to Pay
NIMBY	Not in my backyard
NPV	Net Present Value

NTRE	Non-traditional renewable energy sources
PES	Payment for Environmental Services
SDGs	Sustainable Development goals
SE4ALL	Sustainable Energy for All
S_{Impact}	Social Impact
t of $\text{CO}_{2\text{eq}}$	Tons of carbon equivalent emissions
TW	Terawatt
USD	United States Dollars

1. INTRODUCTION

Demand for energy and associated services, to meet social and economic development and improve human welfare and health is increasing. All societies require energy services to meet basic human needs (e.g., lighting, cooking, space comfort, mobility and communication) and to serve productive processes. Since approximately 1850, global use of fossil fuels (coal, oil and gas) has increased to dominate energy supply, leading to a rapid growth in carbon dioxide (CO₂) emissions. (IPCC, 2012).

According to the Intergovernmental Panel on Climate Change (IPCC) greenhouse gas emissions (GHGs) are undoubtedly the main cause for global warming, and within the largest emitters we can identify the energy sector amounting for 47% of total anthropogenic emissions between 2000 and 2010. (IPCC, 2014). Globally, the energy sector represented 35% of total emissions in the year 2010. A continued increase of fossil fuel use would only drive climate change further. Hence, Costa Rican and international experts expect, this sector to produce the most significant changes for the attainment of sustainable development. This entails significant modifications in both supply and demand within the energy sector.

However, not many countries have aggressively tackled the issue promoting adaptations to the structure of their energy systems by varying inputs, improving efficiency and stability, or reducing consumption. The United Nations General Assembly declared the period between 2014 and 2024 the Decade of Sustainable Energy for All calling upon member states to “galvanize efforts to make universal access to sustainable modern energy services a priority”. Stressing particularly on the importance of improving access to “reliable, affordable, economically viable, socially acceptable and environmentally sound energy services and resources for sustainable development” (United Nations, 2014), thus promoting reduction of poverty, improved health conditions and mobilizing societies towards development.

Costa Rica, a small Central American country has successfully achieved 98.95% generation of electricity based on renewables for the year 2015 and access to 99.28% of the population (IDB, 2016 and Isola Wiesner, 2015). These astonishing results have not been easily attainable for the nation, and ensuring 100% access with 100% renewable sources becomes more and more difficult with a growing population, growing demand and a strong dependence on hydroelectric systems for energy generation in times of extreme climatologic variations. For Costa Rica to reach these goals becomes of great global significance as it provides a beacon to the world that proves

it is possible, and reduces learning curves for other developing nations by providing best practices and tested experiences so that they may leapfrog through the process in search for sustainable development.

During 2007, a series of blackouts drove the Costa Rican national government to promote a national emergency decree. An estimated 10 million USD in losses was suffered in a single blackout. Representatives of the private sector predicted that if blackouts persisted in the next two years, a loss of up to 400 million USD could be incurred, as well as complications in public safety and healthcare which were unpredictable at the moment. (La Prensa, 2001). President Arias responded, during his opening of term speech at the Legislative Assembly: “we have declared a state of emergency that will allow implementation of a management plan for the crisis, to restore to the Costa Ricans the right to continued public service in energy” (Asamblea Legislativa de la República de Costa Rica, 2007). This decree aimed to simplify procedures so that the energy utility company (ICE) could acquire equipment to satisfy demand mainly through fossil fuels, however, after legal consultation with the Comptroller General and experts in the ministry of the presidency, the decree was considered to be potentially illegal and was finally not presented. This situation drove national policy makers and experts to debate on what were the possible and optimum measures to increase production and ensure stability of the entire system. A few months earlier through executive decree N°33487, national government promoted the Peace with Nature Initiative which would provide the legal support for the country to unilaterally announce mid-2007 its goal and strategy to achieve Carbon Neutrality by the year 2021.

With the goal to increase energy production, increase stability and resilience of the system, as well as promote renewable energies that would assist in achieving Carbon Neutrality, the nation proposed a set of strategies that included:

- a. modifying the roles of public and private actors in energy generation;
- b. promote energy efficiency and reduction of consumption,
- c. advance in the implementation of smart grid and distributed/decentralized generation;
- d. improve energy storage, and
- e. increase / diversify energy input from renewable sources.

This study focuses on the last recommendation: increasing and diversifying the energy mix. It does so paying special attention to achieving Carbon Neutrality and Sustainable Energy for All (SE4ALL). In that sense, this project developed a comparative study of all energy sources, current and proposed, to analyze the nation’s possibilities. It pays special attention to Ocean Energies,

one of the least studied and most novel options worldwide which is less dependent on climatic oscillations than hydroelectricity, and to public preference especially relevant in highly legalized nations, such as Costa Rica, that provide many mechanism for civil society to participate in the definition and approval or disapproval of public policies.

1.1. PROBLEM STATEMENT

Based on the analysis of the National Energy Plan 2012-2030, Costa Rica presents a high dependency on a single source for energy production, specifically hydroelectricity that represents ¾ of national production on average. Furthermore, this source is expected to have the largest growth in the coming years to adequately satisfy demands. (MINAE, 2011)

However, due to climate change which causes important variations in rain patterns and precipitation, depending to such an extent on a single source goes against optimum practices of resilience building, increases vulnerability in energy stability, and potentially increases prices as focus is mainly on massive hydro power plants. Significant variations in production from one year to another have forced the nation, during specific periods, to resort to fossil fuel generation to avoid blackouts, thus increasing carbon emissions and taking steps away from Carbon Neutrality. Furthermore, research by the Ministry of Environment and Energy (MINAE) and the national Meteorological Institute (IMN) confirmed Costa Rica as one of the most prominent hotspots for Climate Change in the tropics, predicting a reduction in precipitation and confirming this problem will only grow in complexity in the coming years.

Therefore, identifying the best options to diversify the energy mix to achieve 100% production and supply from renewable energy sources, with resilient and stable systems becomes of utmost relevance. This study aim thus to examine the different possibilities in Costa Rica, with a special focus on ocean energies. The nation is approximately 11 times larger in marine territory than in land territory, and advances in technology to produce energy from this source have caught the attention of the Central American nation. Throughout this study we aim to answer three main questions that are closely related to the achievement of national sustainable development goals (SDGs):

1. Can Ocean Energy play a future role in Costa Rican energy mix?

2. What energy sources could be increased or introduced to improve diversity of energy mix and achieve selected Sustainable Development Goals?
3. What is the public's acceptance of energy sources and how could they impact project viability?

1.2. RESEARCH DESIGN

This study uses a series of research methodologies to respond to the enquiries presented in the problem statement. The first half of the study is conducted from a qualitative approach developed through literature reviews, and a series of short interviews and conversations with experts. While the second half is based on quantitative studies through calculations of Ecological Footprint (EF), Cost Benefit (CB) and Social Impact (S_{Impact}). The aim of this study is to provide a macro overview of the situation and deliver a comparative analysis between the different energy sources currently present in the country as well as ocean energy. This would allow to identify where further research would be most relevant.

For those effects the following structure was determined:

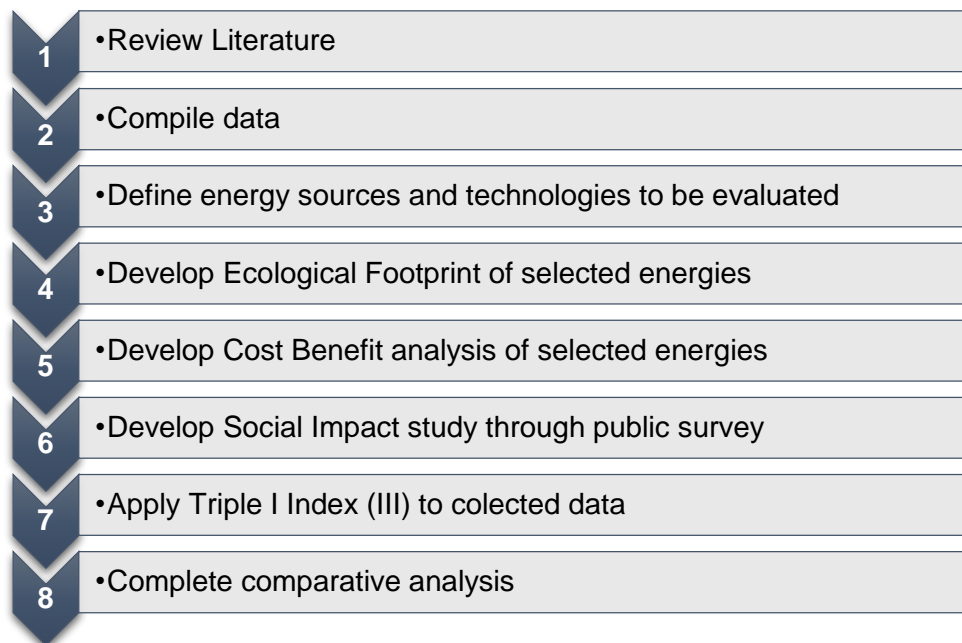


Figure 1 Research structure

Source: developed by author.

This study uses points four through six for individual analysis of the different energy sources. The Triple I index (III) calculated in subtitle 4.5 aims to provide a result simple to understand to deliver a macro view of the energy systems including Ecological Footprint, Cost Benefit and Social Impact developed through a survey utilizing conjoint analysis software to identify public preference of energy sources based on acceptance or rejection of specific impacts of energy sources.

In order to succeed, this study calculated these sections with comparable data that would apply (in general terms) to all of the energy systems. In that sense, project specific data for all measures utilized will not be directly present in this study; results are to be understood as national averages and could present variations in project specific measures. This also presented important limitations as ocean energy is currently nonexistent (beyond pilot projects) in Costa Rica or other comparable tropical ecosystems.

1.3. THESIS FLOW

The present study consists of five chapters where all sections of research design are developed as follows:

Chapter one consists of a brief introduction, and problem definition. In this chapter we can find understanding of the rational for this study, the basic methodological structure followed, and objectives.

Chapter two provides an introduction to the most relevant SDGs for this study and their current state as well as the energy situation in Costa Rica. This study defines, throughout the chapter, Carbon Neutrality in the Costa Rican context, Sustainable Energy for All programs, historical energy situation of Costa Rica, and non-traditional renewable energy sources (NTRE) potentials, for this small nation, including ocean energy.

Chapter three presents an overview of the different energy systems derived from marine sources currently identified, marine climatological conditions, energy source selection, and potential source specific technology to utilize. Additionally, it presents a brief overview of environmental and socio-political conditions for the introduction of the new energy source.

Chapter four consists of a walkthrough of the process followed to conduct a comparative analysis through the calculation of Triple I Index (III): an analysis of currently present energy systems in Costa Rica in terms of Ecological Footprint, Cost Benefit analysis, and Social Impact survey results are presented. The aim of this chapter is to identify in environmental, economic and social terms which energy source has the least impact and highest climate change mitigation potential. Additionally, results for ocean energy in this evaluations are summarized and discussed.

Finally, chapter five concludes this research by presenting mayor discussion points and identifies potentials for future research. It presents reflections of environmental, economic and social aspects for the consideration in next stages of project and policy development.

2. COSTA RICAN SDGs AND ENERGY SITUATION

Present chapter provides an introduction to the most relevant SDGs for this study and their current state as well as the energy situation in Costa Rica. This study defines, throughout the chapter, Carbon Neutrality in the Costa Rican context, Sustainable Energy for All programs, historical energy situation of Costa Rica, and non-traditional renewable energy sources (NTRE) potentials, for this small nation, including ocean energy.

2.1. SDGs RELEVANT TO THIS STUDY

2.1.1. CARBON NEUTRALITY

The Carbon Neutrality goal for Costa Rica became a reality in July 2007 supported by executive decree N° 33487 signed by former president Arias. This decree provided legal and political support to promote a change in the development paradigm from those historically followed by developed nations to a low-carbon development. The goal came as part of a four point commitment assumed in the Peace with Nature Initiative: 1. C-neutrality by 2021 through carbon emissions offset; 2. develop and implement environmental management plans; 3. Increase forest cover and protected areas, expanding the payment for environmental services (PES) system; and 4. Promote Education for Sustainable Development. (Arias, 2007)

Feoli Peña describes Carbon Neutrality in the Costa Rican context through the definitions of UNEP “zero impact to nature, balancing produced and offset emissions within a clearly defined scope (i.e. location, time period)”, and those of the national institute of technical norms (INTECO) who states that through a transparent process of emissions measurement: net emissions, minus reductions and compensations would equal zero. (Feoli Peña, 2013)

Former minister of Environment and Energy Castro states regarding Costa Rican Carbon Neutrality “this would mean that the net balance of greenhouse gases released into the atmosphere by Costa Rica from 2021 onwards would be zero. This does not mean that the country will have zero greenhouse gas emissions; rather it means that emissions will be reduced to the point where offsets are sufficient to cancel all remaining emissions for a net greenhouse gas contribution of zero (in other words emissions [E] minus reductions [R] minus carbon offsets [C] would equal zero, or $E - R - C = 0$). Costa Rica’s adoption of this target reflected the view that Carbon Neutrality could be achieved without compromising the country’s national economic development

goals” (Castro R. , 2015), and presents the disaggregated Equation for Carbon Neutrality, with which the neutrality of each sector or company can be calculated, as:

Equation 1 Carbon Neutrality

$$\sum_{i=1}^n e_i - \sum_{i=1}^n r_i - \sum_{i=1}^n c_i = 0$$

Where:

e_i = company or entity i’s emissions

r_i = company or entity i’s emissions reductions

c_i = company or entity i’s offsets

Emissions are calculated using CO_{2eq} as a measure. Where each GHG is calculated in terms of CO₂. Each gas has a different global warming potential (GWP) which is expressed in its equivalency to CO₂ as follows (i.e 1kg of CH₄ = 25kg CO₂):

Table 1 Carbon equivalent emissions of GHGs

Greenhouse Gas	Formula	100-year GWP (AR4)
Carbon dioxide	CO ₂	1
Methane	CH ₄	25
Nitrous oxide	N ₂ O	298
Hydrofluorocarbon-32	CH ₂ F ₂	675
Perfluoromethane	CF ₄	7 390
Perfluoropropane	C ₃ F ₈	8 830
Perfluorobutane	C ₄ F ₁₀	8 860
Perfluorohexane	C ₆ F ₁₄	9 300
Perfluorocyclobutane	c-C ₄ F ₈	10 300
Perfluoroethane	C ₂ F ₆	12 200
Perfluoropentane	C ₅ F ₁₂	13 300
Hydrofluorocarbon-23	CHF ₃	14 800
Sulphur hexafluoride	SF ₆	22 800

Source: reproduced by author from (Manitoba Eco-Network, 2015).

A consistent support from both public and private sectors have made possible the advancement of this strategy. Government announced in 2014 that after a study conducted jointly with the German GIZ the nation was 81% to the goal (Castro R. , 2014). In 2015, the third government since the establishment of the goal confirmed support for the strategy as stated in the nations Intended Nationally Determined Contributions (INDCs) presented to the UNFCCC. Where, national government states:

“Costa Rica will center its climate change actions on increasing society’s resilience to the impact of climate change and strengthening the country’s capacity for a low emission development on the long term. Costa Rica will strengthen its climate action with efforts in reduction of emission of greenhouse effect gases...

... the country is committed to a maximum of 9 374 000 t CO_{2eq} net emissions by 2030, with proposed emissions per capita of 1.73 net tons by 2030, 1.19 Net Tons per Capita by 2050 and - 0.27 Net Tons per Capita by 2100. These numbers are consistent with the necessary global path to comply with 2°C goal. Costa Rica’s commitment includes an emissions reduction of GHG of 44%, of a Business As Usual (BAU) scenario, and a reduction of 25% of emission compared to 2012 emissions. To accomplish this goal Costa Rica would have to reduce 170,500 tons of GHG per year until the year 2030.” (MINAE, 2015)

Since the year 2009 and confirmed in 2012 with the approval of the National Climate Change Strategy (ENCC in Spanish), a guide to prioritizing mitigation and adaptation actions was established paying particular attention to the following areas:

Table 2 Key sectors defined in the ENCC

Mitigation	Vulnerability and Adaptation
Energy	Hydrological
Transportation	Energy
Agricultural	Agricultural
Industrial	Fisheries and Coastal Areas
Waste	Health
Tourism	Infrastructure
Hydrological	Biodiversity
Land Use Change	

Source: reproduced by author from (MINAET, 2009).

As observed, the energy sector is the only one present both in mitigation, and vulnerability and adaptation; confirming the relevance of this sector in the attainment of Carbon Neutrality. Furthermore, as seen in the following Figures, the energy sector amounts to the largest portion of national emissions.

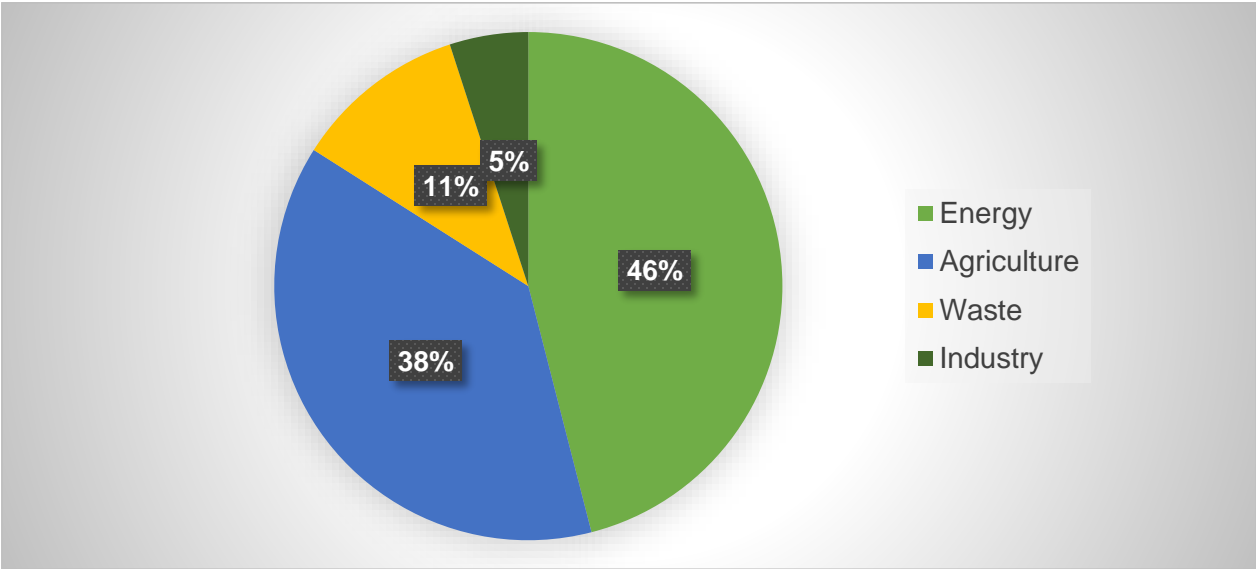


Figure 2 GHG emissions per sector 2009

Source: adapted by author from (Castro R. , 2012).

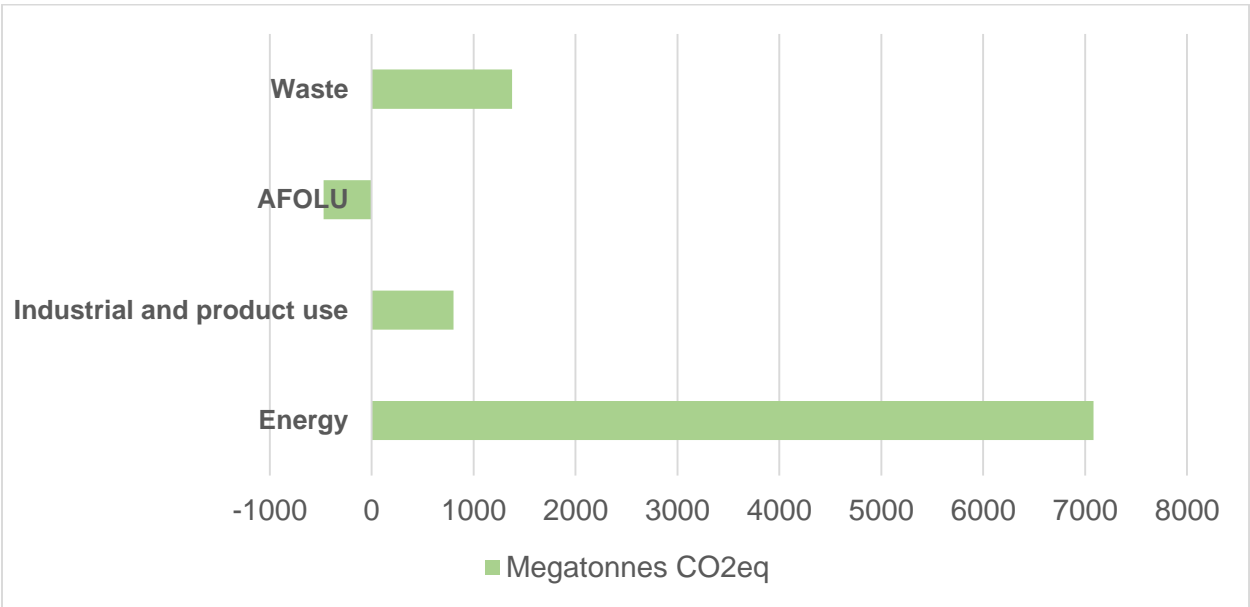


Figure 3 Net emissions per sector 2010

Source: reproduced by author from (MINAE, IMN, 2014).

The remaining 19% of projected emissions by 2021 (about 5 million tons of CO₂ for that year) should be reduced by the sum of public and private projects in the transport, energy, agriculture and industry sectors. (Castro R. , 2014) In the aim for Carbon Neutrality, interventions within the energy sector are the most relevant, and electricity generation has a transverse impact in all areas mentioned by Castro.

That being said, within the energy sector, transportation and industry present the largest carbon emissions and the most complex challenge for the nation, followed by energy generation and residential/commercial sectors where interventions in production, and projects to increase efficiency and reduce consumption can be undertaken.

This study will focus on the attainment of a carbon neutral electricity supply through changes in the energy mix composition by promoting energy generation with 0 net emission projects, be it through reductions or offset.

2.1.2. SE4ALL

According to SE4ALL “The Sustainable Energy for All initiative is a multi-stakeholder partnership between governments, the private sector, and civil society. Launched by the UN Secretary-General in 2011, it has three interlinked objectives to be achieved by 2030:

1. Ensure universal access to modern energy services.
2. Double the global rate of improvement in energy efficiency.
3. Double the share of renewable energy in the global energy mix.”

Costa Rica is one of the 85 developing countries of the total 102 partners in SE4ALL initiative. The nation is amongst the 43 that have submitted the Rapid Assessments/Gap Analyses. In the report, finalized early 2013, a socio-economic focus of poverty eradication through universal access to renewable energy sources prevails.

The country has been highly successful in promoting universal access, however pending communities present significantly higher investment costs which would require social policies from government and the energy sector (national and international) to be undertaken. This in turn provides an optimum scenario for innovation, utilizing small scale, decentralized, renewable energy projects from NTREs. High penetration rate of electric coverage and technical knowhow would facilitate these processes if access to credit is possible. Table 3 summarizes findings from the SE4ALL rapid assessment.

Table 3 SE4ALL goals and current situation in Costa Rica

Current Situation	SE4ALL goals
0.72 % of rural population does not have electricity. Difficulty of access, high dispersion, and distance from public networks are the main barriers.	2015 goal: Complete electric company program to achieve 100% national electricity coverage by providing access to 8 130 isolated rural homes.
Increased thermal generation since 2010 due to hydrological factors. Cost of generation has increased because of this condition.	2021 goal: Reach 100% of electric generation from 100% renewable sources.
Electricity consumption increased at a yearly cumulative growth rate of 4.68% year, from 9 723 GWh in 2011 to 21 589 GWh in 2030.	2021 goal: Reduce by 8.5% the electric consumption from the base 2010 scenario.

Source: Adapted and translated by author from (Blanco R., 2013).

Furthermore, in 2013, 30 201 people still had no access to electric service (IDB, 2016), and based on estimates from (Castro & Cordero, 2003) to provide the service would require an investment of approximately 18 120 600 USD.

Variations in yearly composition of energy mix are attributable in large scale to climate change as growth in production has not been significantly different to that of demand and no mayor projects have been undertaken in the past 5 years to significantly affect composition.

As seen in Figure 4, thermal energy generation peaked during 2013 and 2014, however in the year 2015 hydroelectricity made a strong recovery, attributed to high levels of water flow in main reservoirs. A historically dry 2015 however, predicts that 2016 would not be able to replicate the same results.

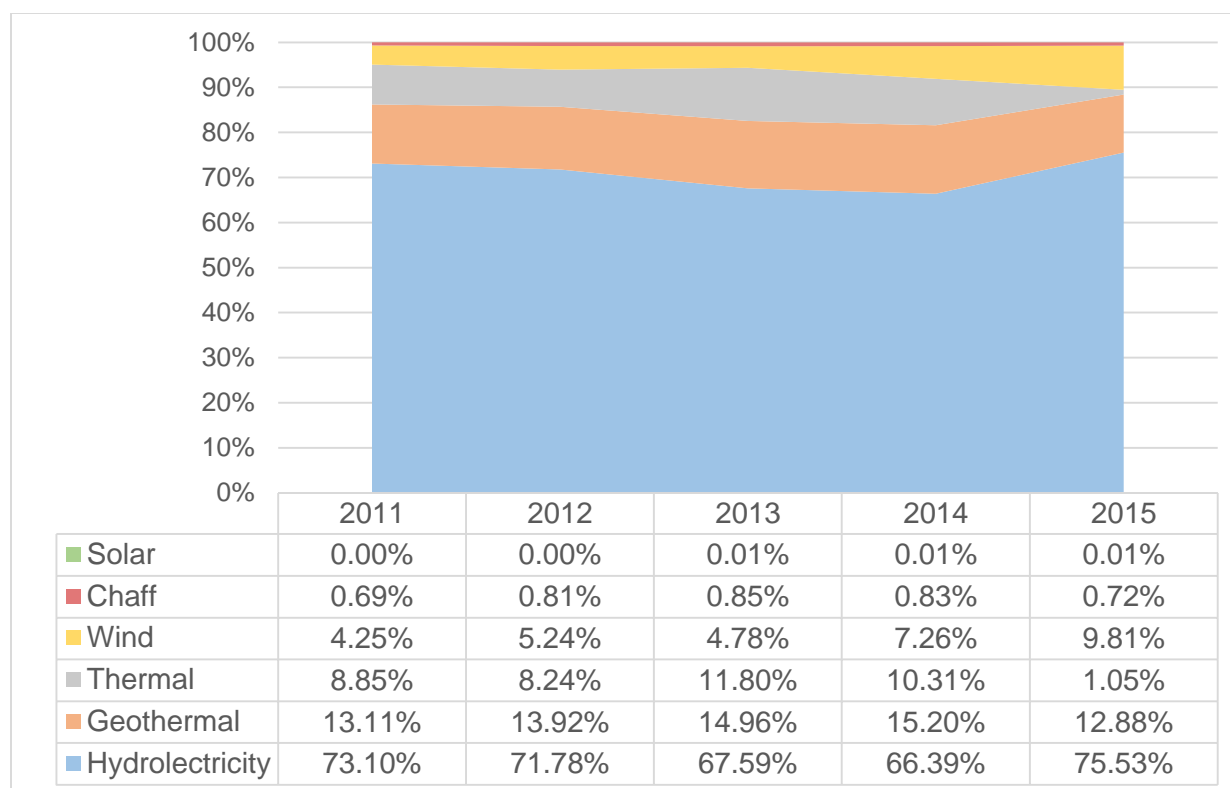


Figure 4 Energy production by source 2011 - 2015

Source: developed by author from annual production and demand reports by ICE.

Table 4 presents national energy potentials both theoretical and identified for renewable energy sources. Amongst those that have the highest theoretical potentials we can identify solar and marine energy. However, these two sources are either miniscule within the energy mix or non-present. High costs, low market penetration, and insufficient technical knowhow are deemed the main reasons for their small role.

Table 4 Theoretical and identified energy potentials

	Theoretical Potential	Identified Potential
Hydroelectric	25 500 MW	6 633 MW
Solar	10 000 MW	0.14 MW
Marine*	8 900 MW	2 500 MW
Geothermal	865 MW	257 MW
Biomass	635 MW	127 MW
Wind	600 MW	274 MW

Source: develop by author with public data from (MINAE, 2011) and (Brito e Melo, 2013).

* Marine potential includes only wave energy, tidal energy and marine currents

Updated sources however, state identified potentials (in MW) for hydroelectricity at 7 034, geothermal 875, wind 894, biomass 122, and solar at 126 (Centro Nacional de Planificación Eléctrica, 2014).

National energy plan 2012 – 2030 states: “Costa Rica has no proven oil and natural gas reserves, and although studies have identified potential reserves, for environmental reasons, exploration of these energies is not included as part of the energy policy. Additionally, the possibilities of using coal reserves are very limited due to high content of volatile sulfur reserves, as well as for environmental and commercial exploitation considerations.” (MINAE, 2011) The same year, the nation consequently signed a two year moratorium on petroleum exploration and exploitation, recently extended until the year 2021.

Nevertheless, utter dependence on foreign resources for the acquisition of fossil fuels, places them in a position of high vulnerability. This situation further confirms the relevance of drastic changes in the transportation sector, and the potential of the electric sector to reduce said vulnerability by eliminating any demand of fossil fuels for electric generation, and potentially generate autochthonous energy sources for transportation such as hydrogen.

2.2. THE ROLE OF ENERGY SYSTEMS IN SDGs

2.2.1. SINGLE SOURCE ENERGY DEPENDENCY

As seen in previous sections, Costa Rica is significantly driven towards the use of hydroelectricity. The source presents the largest theoretical potential and most if not all of government policies promote a significant increase in the installed capacity of hydro projects to satisfy growing demand. Nevertheless, such a high dependency on a single source seems contrary to resilience building and achievement of sustainable development. Additionally large reservoirs and dams are facing an increase in opposition from local communities, for example The Diquis project has been postponed several times due to indigenous and local groups’ resistance.

A closer look to energy generation by source (Table 5) provides insights on the relevance of energy mix diversification. Although increases in energy generation from hydroelectricity are perceived in percentage wise, in reality, production tends towards reduction. This drop in production requires a subsequent reduction in consumption or substitution for other sources to supply the gap in demand. We can clearly see how all additional sources except for biogas (with no reported production in annual reports from 2011-2014) tend towards increase.

Table 5 Energy production by source 2010 - 2014 (MWh)

	2010	2011	2012	2013	2014
Hydroelectricity	7 262 293.50	7 134 623.70	7 233 202.93	6 839 059.31	6 717 152.41
Thermal	641 174.58	863 341.51	830 283.67	1 195 996.52	1 043 203.01
Geothermal	1 176 081.50	1 279 543.48	1 402 551.51	1 516 711.74	1 538 135.68
Chaff	65 326.41	67 629.91	81 626.79	86 322.73	83 625.70
Wind	358 675.27	414 472.99	528 383.62	484 568.95	734 753.38
Solar	0.00	0.00	295.04	1 441.57	1 463.74
Biogas	70.29	0.00	0.00	0.00	0.00

Source: developed by author from annual production and demand reports by ICE.

Growth in electric demand would require in the next decade to increase installed capacity by approximately 2 000 MW (Blanco R., 2013). Furthermore, Government has proposed an increase of 3 420 MW of installed capacity as follows:

Table 6 Capacity additions to the electric system and structure by source for the period 2010 - 2030

Source	MW	%
Wind	154	4.5
Geothermal	175	5.1
Hydroelectric	2 735	80.0
Solar	100	2.9
Biomass	55	1.6
Thermal	201	5.9
Total	3 420	100

Source: reproduced by author from (MINAE, 2011).

“Hydroelectric power will remain dominant in the generation and increase its share from 76.4 % to 80 %. This is consistent with resource availability, reliability energy independence, sustainable development and low emissions presented by the source. Geothermal would remain second in importance but with a reduced stake from 12.4 % to 10.6 %. Wind generation expands its participation from 3.8% to 4%, maintaining its current role as a complement to hydroelectric power due to their greater availability during the dry season. Biomass hold a marginal share of 0.7 % to exhaust the available waste resource. Solar generation will begin its incursion and reach 1.3 % in 2030. Thermal generation from fossil fuels will remain below 5%.” (MINAE, 2011)

Nevertheless, variations in rain patterns and temperature make optimization of hydroelectric generation difficult to consolidate. Stability of the energy system becomes an issue when considering these variables. Figure 5 provides a macro view of accounted changes, where we can clearly appreciate a reduction in precipitation and an important increase in temperatures. This macro summary however, does not fully explain the complexity of the issue, as mayor variations are both in daily terms and in monthly averages throughout a period of time, and are highly relevant to specific locations.

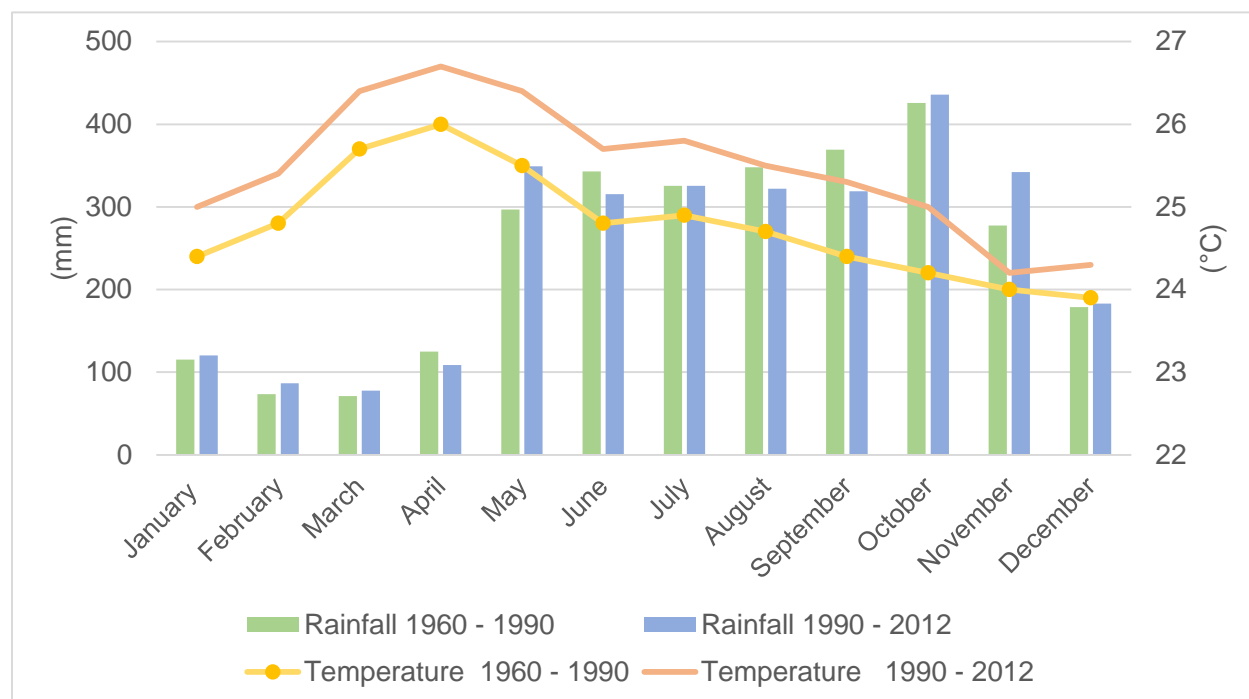


Figure 5 Changes in rainfall and temperature between the periods of 1960-1990 and 1990-2012

Source: developed by author with data from (The World Bank, 2016).

Rainfall predictions for 2080 estimate increases in annual rainfall level of up to 50% in the Caribbean slope; however the Northern Zone specifically in the North Pacific hydrological basins, as most of the Pacific Rim, will have less rainfall than current climate simulations, as far up as 65% (MINAE, IMN, 2012). In simpler terms, the humid region (prone to flooding) will have higher precipitations and the dry region (prone to drought) will receive significantly less rainfall. Adequate management of water resources will be even more complex; current reservoirs like Arenal will be impacted by this reduction in the pacific side.

Added stress on water resources in the northern part of the country would increase currently present social conflicts between competing sectors (i.e. energy, tourism, agriculture). Furthermore, for hydroelectric energy to increase installed capacity by the desired 2 735 MW up to 4 289 MW in 2030, mayor projects would have to be undertaken; projects which would most

likely be concentrated around the Caribbean slope thus placing a significant stress on environmental and socio-cultural resources already at risk, and potentially increasing local opposition to river dams large and small.

Identifying a more sustainable energy mix that could provide stability to the grid without the subsequent stress on environmental and social systems seems to be a reasonable and relevant option for this nation's future. In the following chapters we will further study the potential options in the Costa Rican market.

2.2.2. OCEAN ENERGY AS A POTENTIAL PLAYER IN THE ENERGY MIX

A relatively small nation consisting of 51 100 km² of land territory, the Central American nation possesses coastal areas both in the Pacific Ocean and the Caribbean Sea. This particular condition provides access to approximately 1 500 km of coastal line, 1 254 km on the Pacific and 212 km in the Caribbean coasts. Additionally, ownership of Coco Island has extended marine territory significantly, providing approximately 589 000 km² of sovereign marine territory. National government is continuously working on the adequate identification of all oceanic territory, as many boundaries are still undergoing international negotiations.

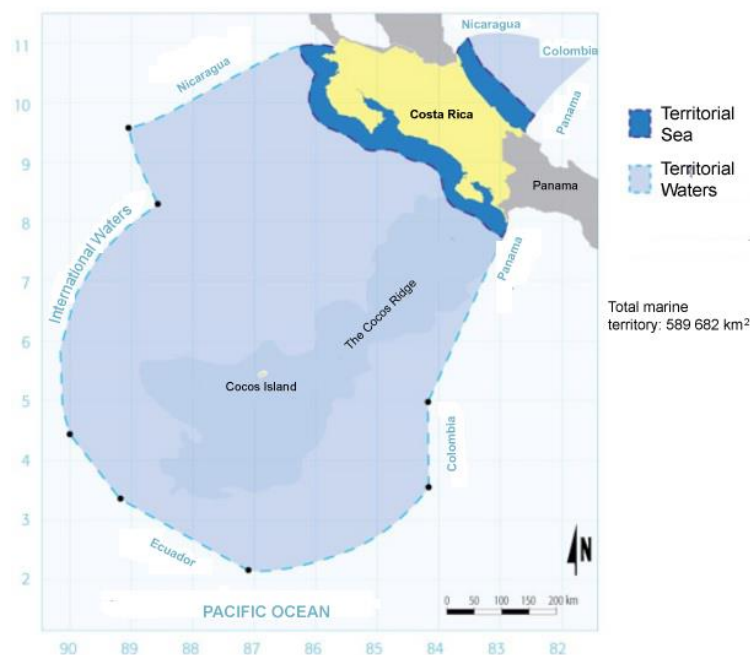


Figure 6 Costa Rican Exclusive Economic Zone

Source: adapted and translated by author from (Castro Truque, 2011).

Besides typically accounted benefits that oceans provide such as fisheries, commerce, and tourism the nation has recognized benefits in climate regulation through carbon sequestration, energy generation, and biological conservation (Tribunal Ambiental Administrativo, 2014). After significant success in conservation in land, particularly through reforestation programs, Costa Rica turned its attention towards the blue areas: rivers, mangroves and oceans.

As one of the nations that has ratified the Convention on Biological Diversity (and subsequent agreements) a commitment to protect at least 10% of territory was assumed. Nevertheless, extension of territory and insufficient funds make adequate accounting of marine conditions, and biological wealth difficult. This results in a high potential of under accounting of marine ecosystem services and biological capacity. Important studies have been undertaken, particularly on biological resources in conservation efforts of sharks, sea turtles and marine mammals, as well as coral reefs and mangroves, ensuing an increase of marine protected areas, and declarations of RAMSAR and World Heritage sites. Coco Island, home to the nation's largest marine protected area is an internationally recognized shark sanctuary. Main risks on marine ecosystems come from unsustainable fishing practices (i.e. trawling, over fishing), pollution, waste management, and coastal degradation (Tribunal Ambiental Administrativo, 2014).

However, the country needs to conduct further studies on climate change mitigation actions and sustainable use of marine resources. A quick view on wind, wave, and tidal patterns presented the possibility to utilize the immense marine territory for generation of energy. Analyzing climate data available at the moment, Vega Argüello estimated energy potentials from wave energy as seen in Table 7. Current energies were not estimated because conditions were not considered favorable; other potential marine energy sources were not analyzed.

Table 7 Predicted wave power potential

	Power (kW/m)
North Pacific	23 085
Central Pacific	20 846
South Pacific	21 426
Caribbean	13 049

Source: reproduced by author from (Vega Argüello, 2010).

During an official diplomatic visit to Japan, the commission led by former president Chinchilla participated in the Renewable Energy World Fair 2011. According to former Costa Rican Ambassador to Japan Cedeño, the commission showed a particular interest in ocean energy systems and the possibility to analyze conditions for Costa Rica to venture into ocean energies. It was clear at that moment; however, that research was insufficient for the definition of baseline scenarios. In the coming year a public bid was presented to determine the potential of marine energy for electricity generation in Costa Rica, financed by the InterAmerican Development Bank (IDB) and commissioned by ICE.

Finally, in 2013, the Cabinet members of the National Sea Commission enacted the national marine policy stating as its main objective: “The Costa Rican government promotes strengthening livelihoods of coastal communities and supports sustainable productive alternatives in marine and coastal areas, related, at least to fisheries, aquaculture, tourism, energy, transportation and culture.” (CONAMAR, 2013) Therefore, formally opening the possibility to study and eventually develop ocean energy in Costa Rica.

3. OCEAN ENERGY: SOURCES, IMPACTS AND SELECTION

Chapter three presents an overview of the different energy systems derived from marine sources currently identified, marine climatological conditions, energy source selection, and potential source specific technology to utilize. Additionally, it presents a brief overview of environmental and socio-political conditions for the introduction of the new energy source.

3.1. ENERGY SOURCES

Energy derived from the marine systems come from four distinct sources: ocean energy, offshore wind energy, geothermal energy derived from submarine geothermal resources, and bioenergy derived from marine biomass, particularly ocean-derived algae. (Abad Castelos, 2014) Ocean Energy, the focus point of the current research is based on renewable sources derived from: waves, tidal range, tidal currents, ocean currents, ocean thermal energy conversion (OTEC), and salinity gradients.

Although a growing interest for offshore wind has been perceived both locally and internationally, at the moment of publication of this research no significant studies had been finalized, and therefore was not included in the study.

In the IPCCs special report on renewable energies, the theoretical potential for ocean energy technologies is stated at 7 400 EJ/yr, well exceeding current and future human energy needs (IPCC, 2012). Furthermore, of the six sources, OTEC is considered to have the largest potential, followed by wave energy. However, except for tidal range systems, most other technologies are still in prototype stage. High transmission costs persist as one of the biggest economic barriers to tackle, especially for systems located furthest from coastal areas. Most technology developments and therefore testing have come from developed nations within the northern hemisphere.

3.1.1. WAVE ENERGY

“Wave energy derives from the transfer of the kinetic energy of the wind to the upper surface of the ocean.” (IPCC, 2012) Globally, a theoretical wave potential is estimated to be 29 500 TWh/yr when considering the technical developments of different technologies. In Central America, theoretically there is a potential of 1 500 TWh/yr. This is the second smallest potential for any

region, only above the Mediterranean Sea and Atlantic Archipelagos. Waves are considered to be highly efficient in transferring energy. Variations in size and period are the result of wind speed, length of wind blow period, and area over which the wind blows. According to (Lizano R., 2007) the wind in Costa Rica's Caribbean coast blows predominantly in northeastern direction throughout the year, this wind in turn is projected to the North Pacific region generating high wave conditions. The central and south pacific regions however, are influenced by strong wind trades in the boreal winter. The Caribbean region presents relatively short wave periods (7s) and crests. On the other hand, waves in the Pacific side are smoother with long wave crests. Figures 7 and 8 present wind and wave conditions in Costa Rica as identified by Lizano.

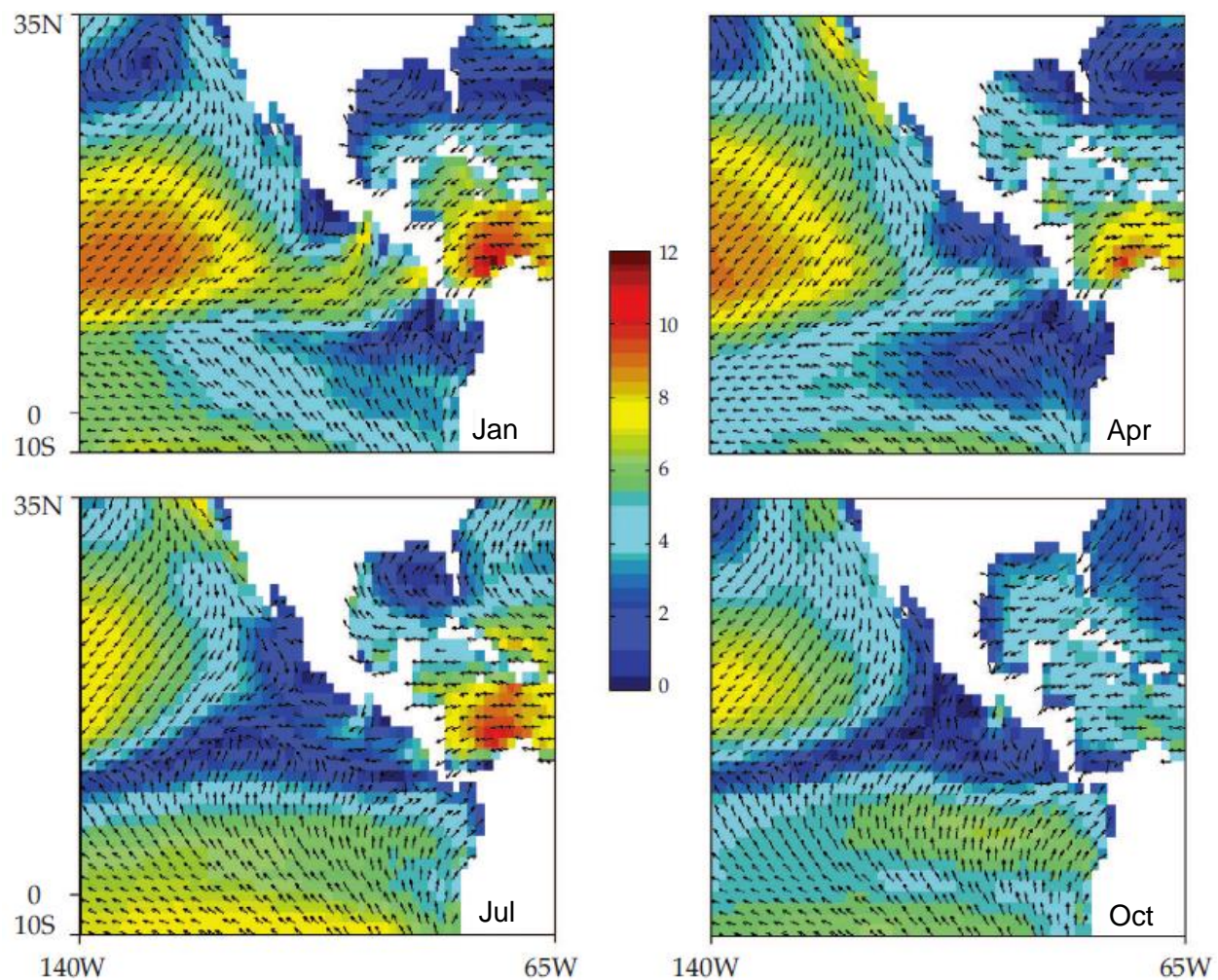


Figure 7 Spatial distribution of magnitude (m/s) and wind direction

Source: adapted by author from (Lizano R., 2007).

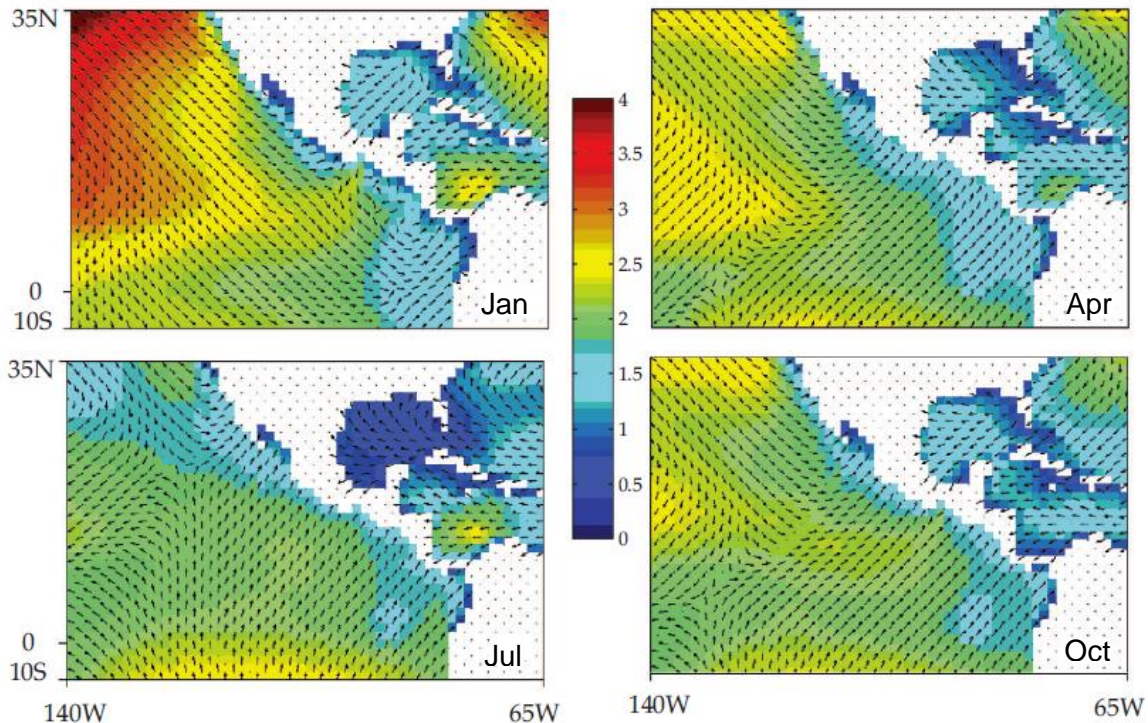


Figure 8 Spatial distribution of wave height (m) and direction

Source: adapted by author from (Lizano R., 2007).

Nevertheless, as stated by IPCC, the region does not fall within the areas with highest mean power. This does not indicate that the energy could not be produced in the region. But, more that special attention must be placed to which technologies would be optimum to efficiently exploit the source. Exhaustive studies must be conducted for this.

3.1.2. TIDAL RANGE AND TIDAL CURRENTS

“Tidal Range (tidal rise and fall), derived from the gravitational forces of the Earth-Moon-Sun system.” (IPCC, 2012) This system is highly similar to traditional hydropower, electricity is produced utilizing the gravity driven inflow, outflow or both. Additionally, in response to the rise and fall of tides, currents are generated which can also be utilized for energy generation. Both tidal ranges and currents are highly predictable even if power is not. The systems are considered to be low risk options because they are not significantly affected by climate change. “The world’s theoretical tidal power potential (tidal range plus tidal currents) is in the range of 3 TW with 1 TW located in relatively shallow waters.” (IPCC, 2012)

As seen in Figure 9, the area of the Pacific Coast of Costa Rica that was measured presents semidiurnal tides with cycles of approximately 12 hours. On the other hand, the area measured on the Caribbean coast is significantly more varied with a diurnal predominance. Tidal ranges in a series of stations measured along the pacific coast went from 2.07 and 2.34 m, in the Caribbean was just of 0.21 m. A minimum tidal range (difference between mean high and low tides) of 5 m is required for plants using conventional hydroelectric equipment. However, some adapted system have been able to produce energy in areas with variations as low as 2 m. (Bharathan & Zangrando, 2007)

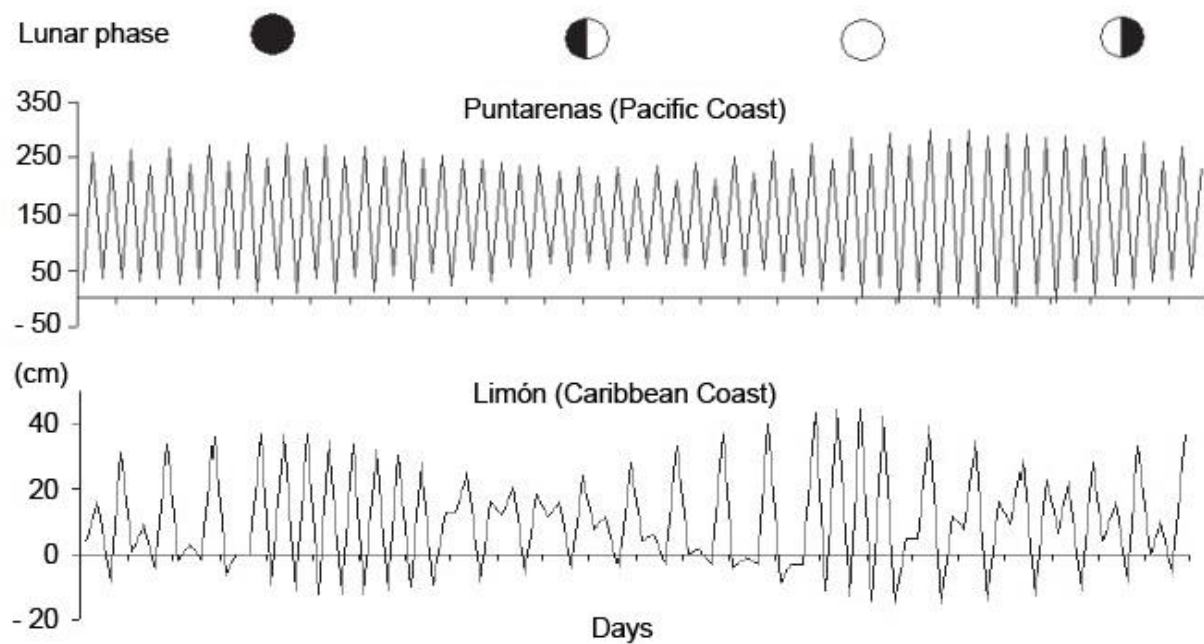


Figure 9 Predicted tides during June 2005

Source: Adapted by author from (Lizano R., 2006).

3.1.3. OCEAN CURRENTS

“Ocean Currents, derived from wind-driven and thermohaline ocean circulation.” (IPCC, 2012) This energy source consists in the exploitation of force derived from the velocity of marine currents in the deep ocean; the source is considered to be highly consistent.

However, according to Vega Argüello and as perceived in global ocean current maps, Costa Rica is not in proximity to any major currents. For this source to be utilized in the country, currents of lower magnitudes would have to be identified.

3.1.4. OCEAN THERMAL ENERGY CONVERSION

Ocean Thermal Energy Conversion (OTEC), derived from temperature differences between solar energy stored as heat in upper ocean layers and colder seawater, generally below 1,000 m. (IPCC, 2012) OTEC is considered to have the highest theoretical potential, between 30 000 and 90 000 TWh/yr, as roughly 15% of total solar input is retained in ocean surface. Additionally, it presents favorable conditions to provide stability to the electrical input as the source is continuously available and presents low variability. Recently the possibility to develop ocean carbon sequestration in parallel to OTEC systems has begun raising awareness, and although unlikely, could potentially become a differentiating factor in stabilizing global carbon emission. A difference of about 20° between surface temperature and deep water is required.

OTEC can be exploited through closed and open cycle system. The difference being that the first utilizes seawater to vaporize and later condense fluids such as ammonia in a closed loop system that will turn a turbine. While in the second, warm seawater is evaporated in a vacuum chamber producing steam that is later condensed utilizing cold seawater. (Bharathan & Zangrando, 2007)

Costa Rica is believed to have an important potential in OTEC alongside other nations with access to the Caribbean Sea. As seen in Figure 12, initial measurements have found relevant variations in ocean temperature between the required depths. Nevertheless, the energy generation capacity of these areas has not been confirmed. Studies to determine potential are under consideration, although, potentially high transmission costs persist as a negative aspect of relevant weight to consider.

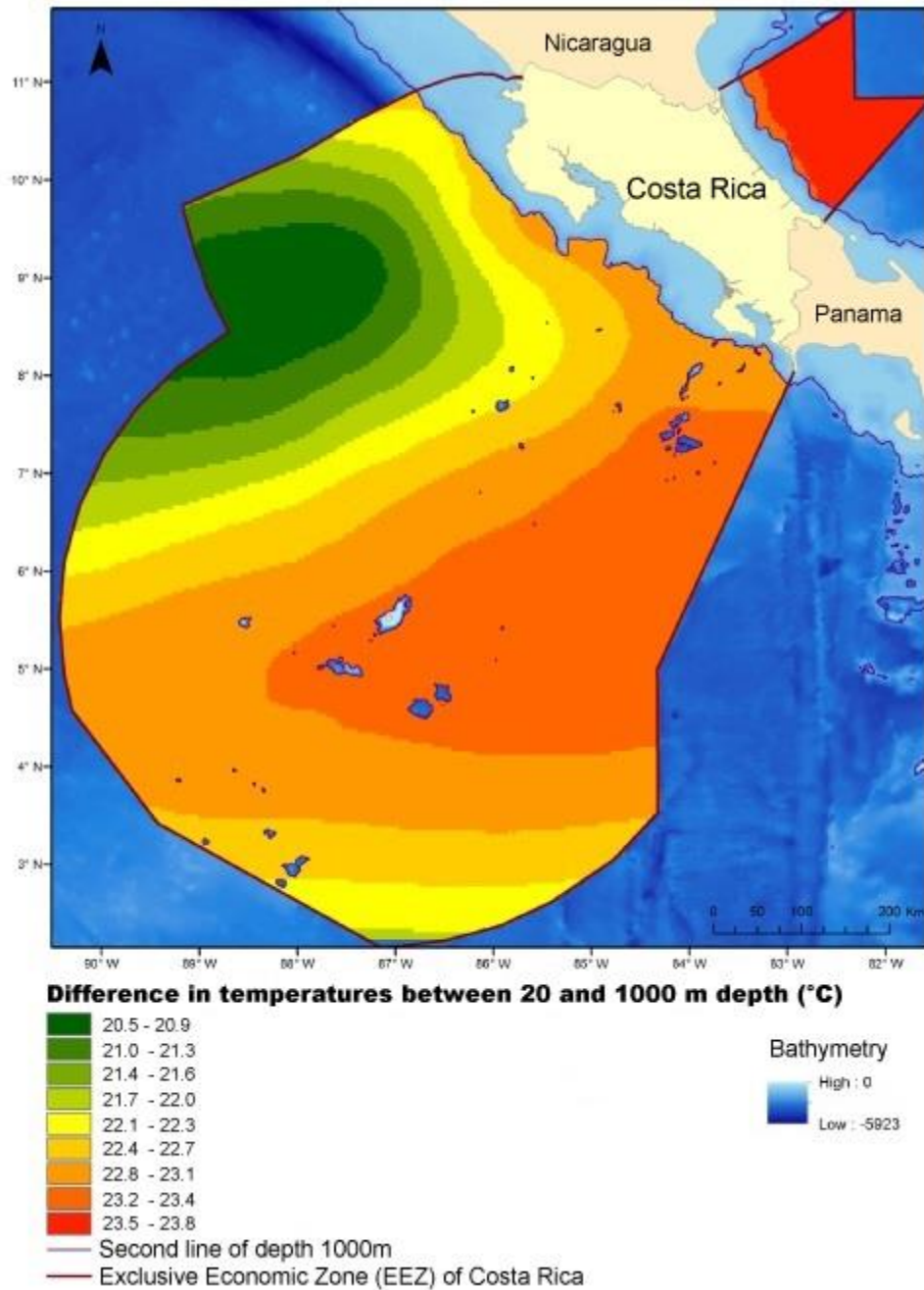


Figure 10 Difference in temperatures between 20 and 1000 m depth (°C) in the Costa Rican Exclusive Economic Zone

Source: adapted and translated by author from (Brito e Melo, 2013).

3.1.5. SALINITY GRADIENTS

Salinity Gradients (osmotic power), derived from salinity differences between fresh and ocean water at river mouths. (IPCC, 2012) Energy is produced from the resulting heat produced by mixing both water sources. This system has an estimated technical potential of 1 650 TWh/yr. This source however, is the least studied in the national context.

3.2. ENVIRONMENTAL AND SOCIO-POLITICAL CONSIDERATIONS

As all energy sources, ocean energies present both positive and negative impacts on environmental and social systems. Nevertheless, since at this point in time most ocean energy projects are only on pilot stages thorough research on potential impacts must be undertaken. Furthermore, as stated in title 3.1, most experiences are concentrated on developed nations in the northern hemisphere where biological, climatological and socio-economic conditions are significantly different from those of countries closer to the equator such as Costa Rica (located at 8° north). Thus research specific to the tropical context and that of developing nations is of utmost relevance. Additionally, ocean energy projects have lifespans ranging from 25 to 100 years; long term impacts must be taken into consideration. “Filling the existing knowledge gap requires testing the devices in situ “and monitoring and evaluating their impacts, taking into account the precautionary approach.” (Abad Castelos, 2014) Still, these studies provide important insights on potential issues and advantages the systems provide.

In general terms, since ocean energies produce no carbon emissions during generation (except for OTEC that has a significantly low emissions factor) the potentials for climate change mitigation are substantial. They provide much needed alleviation of stress on land electric generation and in most cases require no displacement of population, both highly relevant issues in the region, especially so in the case of large hydroelectricity dams. Exclusion of areas for ocean energy farms in line with sustainable coastal management plans, can produce an increase in wildlife refuges and provide net benefits to fishery resources. (House of Commons, 2001)

Additionally, job creation is viewed as one of the main economic factors. To this consideration we must also evaluate the added value of coastal livelihoods diversification and the subsequent improvement on quality of life from reductions in competing human activities (i.e. illegal and unsustainable fisheries, or drug trafficking) in the area. Tidal range systems could serve a double purpose of generating electricity and providing routes for transportation. Finally, increased access to energy services, especially for isolated coastal communities.

On a negative note, amongst undesirable impacts we can identify potentials of sediment transport and deposition, ocean surface acidification, and alteration of benthic habitats. Exploitation of the source could potentially lead to reductions of marine current velocities or wave height. Death or changes in fish and mammal behavior, as well as interference in marine biological cycles (i.e. spawning, feeding, and migration) could also be a result; however there is no evidence to date to confirm this. Nevertheless, lack of evidence could be because of small scale of projects currently undertaken or because in fact impacts are negligible; further testing is required. A potential release of toxic chemicals resulting from spills, leaks or accumulations of metallic and organic components. Environmental impacts are considered in most cases to be most disruptive during construction periods, while electric generation would have mostly negligible impacts. (Abad Castelos, 2014)

More specifically, wave energy has low potentials of producing visual impacts that could affect bird migration routes, feeding and nesting; both issues have been deemed negligible. Alteration of ocean circulation and net mass transport from ocean current systems is unlikely due to small scale of energy systems. Furthermore as stated in the House of Commons report of 2001, “the adverse environmental impact of wave and tidal energy devices is minimal and far less than that of nearly any other source of energy, but further research is required to establish the effect of real installations.”

Initial investment costs are substantially higher than those of most energy sources. This would imply that for projects to be undertaken, important subsidies and loaning structures would have to be in place during initial stages of projects. Current installation and unit costs may prove to be unsustainable from a cost/benefit perspective.

Nevertheless, ocean energies, together with solar PV are expected to have the most significant cost reductions in Costa Rica during the upcoming years as technology is further developed and becomes universally accessible in the market. This predicted trend can be visualized in Figure 11 in terms of % reduction over initial investment and in \$/kW.

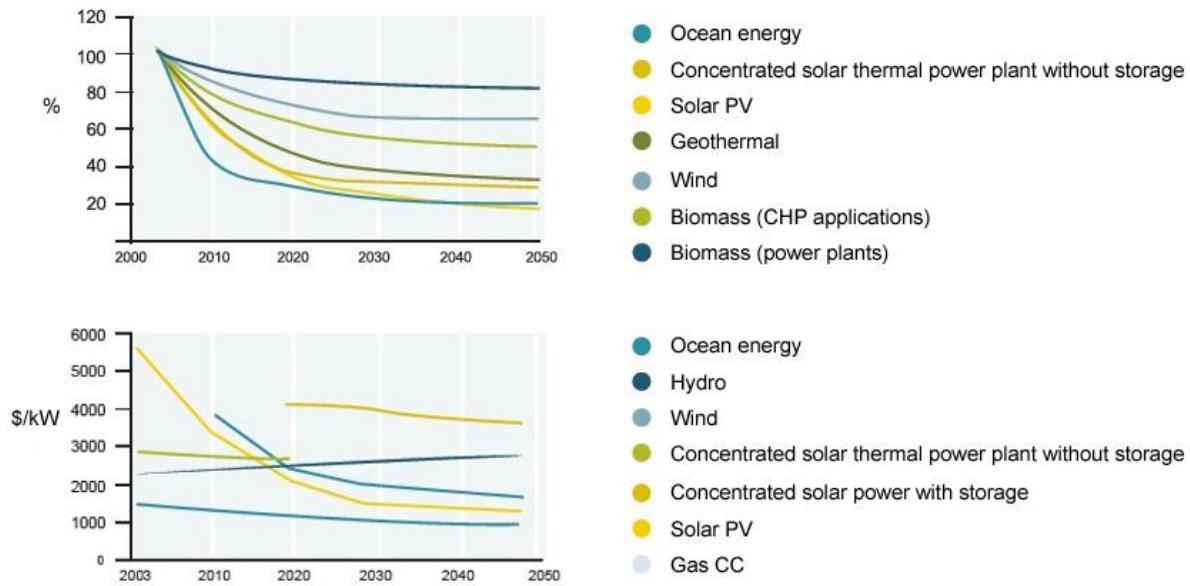


Figure 11 Development of investment costs of renewable energies (standardized to current costs)

Source: adapted by author from (CABEI, 2009).

From a regulatory perspective, the Costa Rican electric market presents a series of challenges. Mainly, general electricity law does not exist to clearly establish general principles for all stakeholders, and has developed specific laws for individual actors (CABEI, 2009). Additionally, in comparison to other regulated service, the institutional framework and policies surrounding the energy sector are considered much more complex and formal. (Hess A., 2014) Law N° 7200 for the Authorization of Autonomous or Parallel Electric Generation of 1990, sets a limit on energy supply from private actors and local cooperatives to the national energy system at 15%, stressing public companies to provide a minimum of 85% of total generation.

No laws for electric generation cover ocean energies specifically. Nevertheless, as stated in article 121, point 14 of Costa Rican Political Constitution, the Legislative Assembly has exclusive powers to “Order the disposal or public use of property that belongs to the Nation” such as marine territory within the exclusive economic zone. However, it also states that: “The following property may not be permanently removed from State ownership: a. Any power that may be obtained from public waters within the national territory; ...” (Legislative Assembly of the Republic of Costa Rica, 1949).

We can infer that ocean energies would fall under this restriction and thus, electric generation from the source would fall under Law N° 8723 “Concession for the use of hydraulic power for

hydroelectric generation” of 2009 for projects within the limits established in Law N° 7200; those that surpass established limit would require constitutional approval by the Legislative Assembly. No specific laws to regulate interaction between coastal communities and organizations developing their economic activity in the oceans with that of electric generation from the source were identified. Until said relations are clearly delimited, a series of legal interpretations and assumptions could drive development of the market; making it vulnerable to policy changes.

“The Costa Rican electricity sector is characterized by the presence of a dominant state, the Costa Rican Electricity Institute (ICE). Wholesale market does not exist in Costa Rica. Competition levels are low, because the sector is based on a non-competitive market model. (CABEI, 2009) Tariff fixation therefore is highly influenced by the operational costs of ICE. Nevertheless, this provides the opportunity to tackle diversification of the energy mix from a socio-environmental perspective less influenced by market costs and more on public policies.

Amongst the most relevant stakeholders in the energy sector identified in (CABEI, 2009), (Comisión para la Gobernanza Marina, 2012), and (Hess A., 2014) we can find:

1. The Costa Rican Institute of Electricity (ICE) and its subsidiary, the National Company of Power and Light (CNFL).
2. Municipal electric companies: Public Services Company of Heredia (ESPH), and the Administrative Board of Cartago Electric Service (JASEC).
3. Cooperatives of rural electrification COOPELESCA R.L, COOPESANTOS R.L, COOPEGUANACASTE R.L, COOPEALFARORUIZ R.L founded in 1989 to produce electric generation from renewable sources.
4. The Regulatory Authority for Public Services (ARESEP): in charge of tariff fixation and to ensure compliance with the quality, quantity, reliability, continuity, timeliness and optimum performance standards.
5. Ministry of Environment and Energy (MINAE) additionally, a vice ministry of oceans has been recently added to this ministry.
6. Ministry of Economy, Industry and Commerce (MEIC) assuming a role in the promotion of competition and the protection of consumers.
7. Ministry of Planning and Economic Policy (MIDEPLAN) in establishment, coordination, and evaluation of national strategies.
8. The Office of the Ombudsman (Defensoría de los Habitantes) as a supporting office to ensure the rights of citizens.
9. The Costa Rican Association of Power Producers (ACOPE).

10. Worker unions within the main electric utility company, mainly the Union of Industrial, Communications ,and Energy Employees (ASDEICE), Union of Professionals and Engineers of ICE (SIICE), and Internal Front Workers (FIT).
11. Business organizations such as Costa Rican Association of Large Energy Consumers (ACOGRAE), Costa Rican Union of Chambers and Associations of the Private Business Sector (UCCAEP).
12. Ecologist groups and conservation organizations the likes of Costa Rican Conservation Federation (FECON), Central American Regional Association for Water and the Environment (ARCA), Flora and Fauna Preservation Association (APREFLOFAS), the International Union for Conservation of Nature (IUCN), the National Alliance for the Defense of Water, and the Environmental Federation of Costa Rica.

Additionally, when considering the possibility to introduce ocean energies in Costa Rica, specific fisheries and marine organizations must be taken into consideration. Such institutions include the Center for Research in Marine Sciences and Limnology (CIMAR) at the public universities, and the Costa Rican Institute of Fishing and Aquaculture (INCOPECA).

3.3. SOURCE AND TECHNOLOGY SELECTION

This subtitle summarizes the public results published in (Brito e Melo, 2013) and (Rojas Morales, 2014), the first thorough approximations to determine theoretical gross potential of marine energy for electricity generation in Costa Rica. The study focused on: wave energy, tidal energy and marine currents¹. Wave energy potential is significantly higher, than those of the other sources. Furthermore, based on demand growth calculations for the coming years, it was deemed that installing only 10% of wave power would be sufficient to supply 17% of energy needs of Costa Rica up to 2035. Three buoys are to be installed, as result of this study, to further elucidate oceanic conditions, and potentially introduce first pilot projects in the coming years.

3.3.1. WAVE ENERGY POTENTIAL

Each coast presented significantly different characteristics, with the western coast, influenced by the south pacific, being deemed the more appropriate of the two for wave energy extraction purposes. “The average value of the wave power in the EEZ in the Caribbean Sea is 9.1 kW/m and off the Pacific Coast is 15.9 kW/m. A SW-NE oriented band in which the wave power levels are clearly inferior is observable across the Pacific EEZ.” (Brito e Melo, 2013)

Theoretical potential excluded Protected Marine Areas, marine areas for responsible fisheries, submarine cables or ducts zones, entrances to main ports and shipping routes, depths inferior to 50 m and superior to 200 m. Farm sites were selected utilizing multi-criteria geo-spatial analysis. Through bathymetry analysis and computational simulations the potentials where defined as established in Table 8. In Figure 14 we can identify the zones most and least apt for energy generation.

Table 8 Estimated resources for the production of electricity from waves

Body of Water	Theoretical Gross Potential		Theoretical Available Potential		Technical Potential	
	GW	TWh/yr	GW	TWh/yr	GW	TWh/yr
Pacific Ocean	13.8	12.3	5.6	48.8	1.7	14.8
Caribbean Sea	1.7	15.0	1.1	9.5	0.3	2.9
TOTAL	15.5	136.3	6.7	58.3	2.0	17.6

Source: reproduced by author from (Brito e Melo, 2013).

¹ Although not analyzed, short notes on OTEC, offshore wind and river currents potentials were presented.

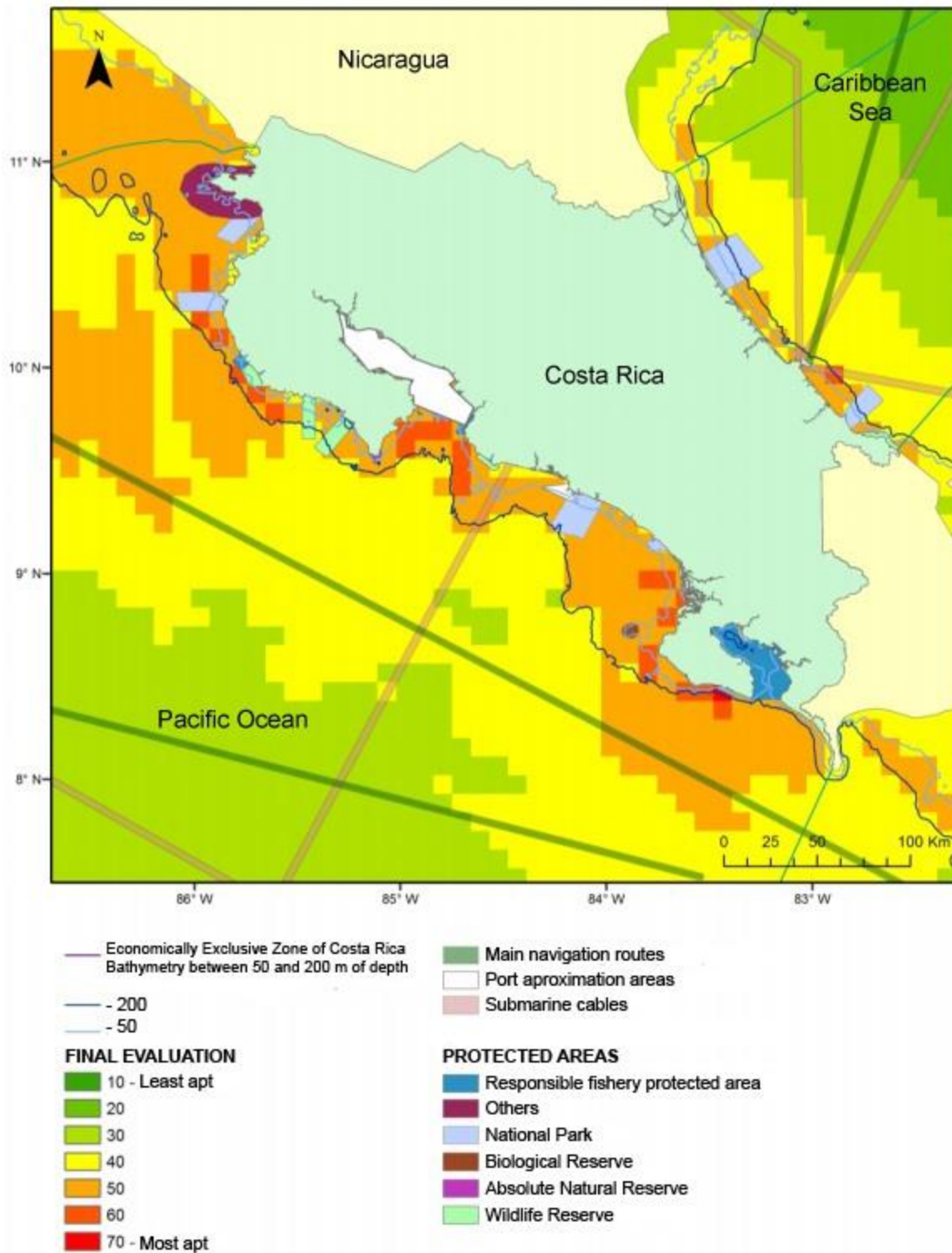


Figure 12 Prioritization of areas for the development ocean wave energy projects and excluded zones

Source: Adapted and translated by author from (Brito e Melo, 2013).

3.3.2. TIDAL ENERGY AND TIDAL CURRENTS POTENTIALS

In regards, to tidal energy, the highest value for tidal range identified was 3.3 m, considered to be insufficient for energy extraction. Although as mentioned in title 3.1.2, technology advances are aiming to utilize ranges of as little as 2 m, the authors did not share this consideration. Therefore tidal energy potentials are not calculated.

Two gulfs, Dulce and Nicoya, were considered in the analysis of potentials in Tidal Energy. The calculation of potentials is based on the principle that the energy extracted is proportional to the square of the amplitude of the tides.

As regards tidal energy it was verified that the tidal range is inferior to 5 meters. The highest value found was 3.3 m in the Dulce Gulf, which is considered to be too low for energy extraction purposes. Tidal energy technology uses conventional components, and it is not expected that technological advances in this field will allow considering tidal amplitude values below the above mentioned 5 m to be used in energy extraction.

Calculated as:

Equation 2 Tidal currents

$$P(t) = \frac{1}{2} \rho g h^2(t)$$

Where:

$$\rho = 1025 \text{ kg/m}^3$$

$$g = 9.81 \text{ m/s}^2$$

Resulting:

Table 9 Estimated resources for the production of electricity from tidal currents

Tidal Current	Theoretical Potential		Technical Potential	
	MW	GWh/yr	MW	GWh/yr
Gulf of Nicoya	1.4	12.0	0.3	2.6
Dulce Gulf	0.8	6.9	0.2	1.5
TOTAL	2.2	18.9	0.5	4.1

Source: reproduced by author from (Brito e Melo, 2013).

3.3.3. OCEAN CURRENTS POTENTIAL

“Ocean currents tend to be slower than tidal currents, with continuous or quasi-continuous flow. Therefore, lower peak velocities (in the order of 1.2-1.5 m/s) can be economically viable.” (Brito e Melo, 2013) Three currents were analyzed, utilizing Equation 3 based on the kinetic energy extraction principle to calculate velocity. For the calculation of the average power Fraenkel’s formula (Equation 4) was utilized. Average velocities for the three sites where: The North Equatorial Counter Current (NECC) 0.23 m/s; The Costa Rica Coastal Current (CRCC) 0.18 m/s; and The Colombia-Panama Gyre 0.56 m/s. Figure 15 shows current velocity surrounding Costa Rica; it is clear that the Colombia-Panama Gyre in the Caribbean Sea provides the highest velocities in the closest proximity to land.

Equation 3 Kinetic energy extraction

$$P = \frac{1}{2} \rho A V^3$$

Where:

ρ = fluid density

A = cross-sectional area of the fluid in a current tube

V = fluid velocity

Equation 4 Average current power

$$P = \frac{1}{2} \rho A K_s K_n V_{peak}$$

Where:

K_s = velocity factor

K_n = neap tides / spring tides factor

V_{peak} = maximum velocity of spring tide

Resulting:

Table 10 Estimated resources for the production of electricity from marine currents

Marine Current	Theoretical Potential		Technical Potential	
	MW	TWh/yr	MW	TWh/yr
The Colombia-Panama Gyre	127.4	1.1	29.2	0.3
North Equatorial Counter Current (NECC)	8.8	0.08	2	0.02
The Costa Rica Coastal Current (CRCC)	4.2	0.04	1	0.01
TOTAL	140.4	18.9	32.2	0.3

Source: reproduced by author from (Brito e Melo, 2013).

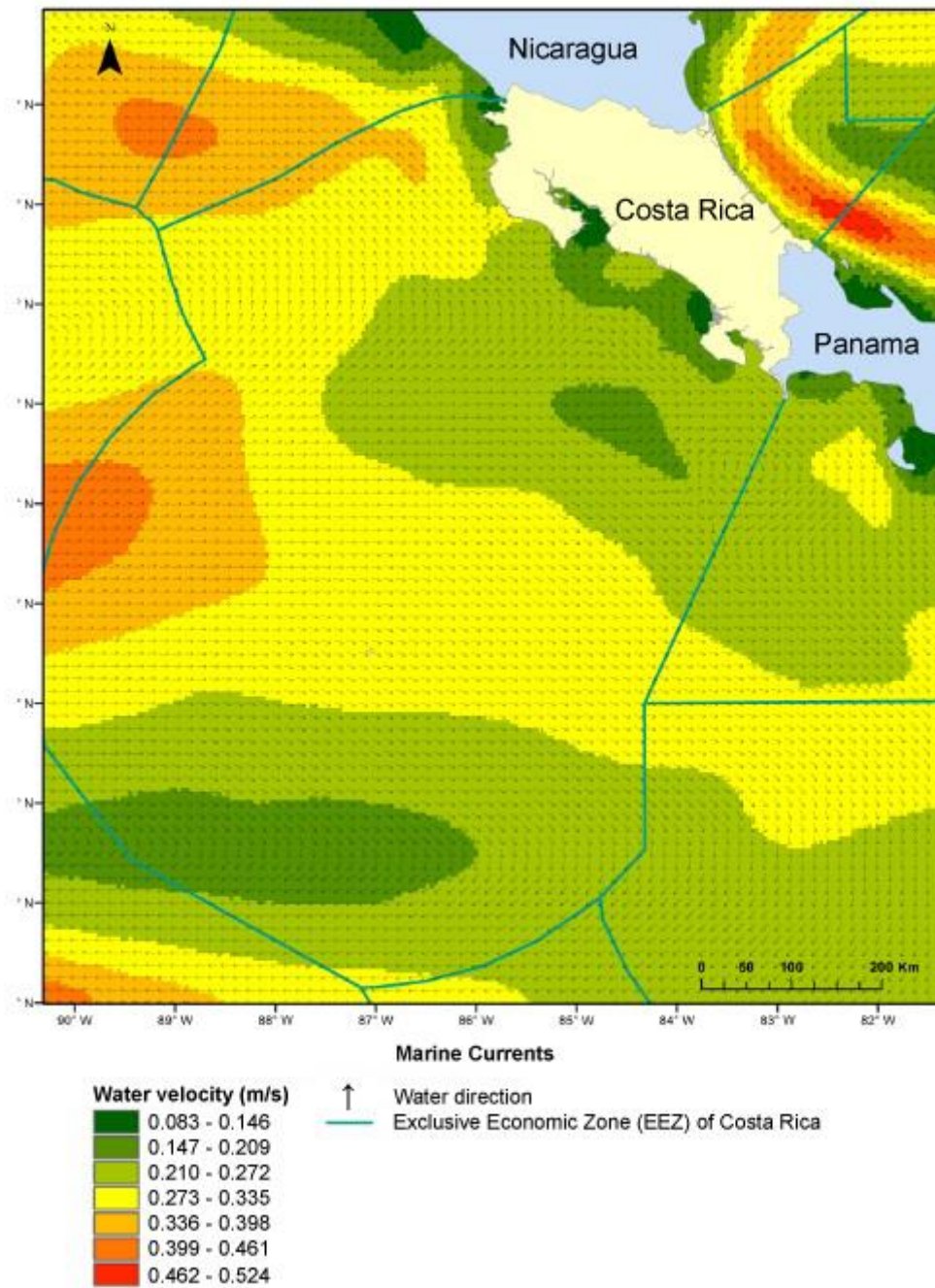


Figure 13 Average velocities and direction of currents at 40m depth

Source: Adapted and translated by author from (Brito e Melo, 2013).

3.3.4. TECHNOLOGY SELECTION

Having defined the technical potentials, and determining to advance in the prospective development of wave energy, a short summary of potential technologies is presented. Three type of systems exist to be utilized either at shoreline, near shoreline areas with depths of 10 – 25 m or offshore, which are (Figure 16): Oscillating power converters (OWC) were waves generate the movement of a water column in a partially submerged compartment extracting energy from the subsequent release of air, Floating/oscillating bodies were energy is extracted from the wave generated movement of a body, and overtopping systems that utilized differences between water levels of an elevated water deposit and the ocean.

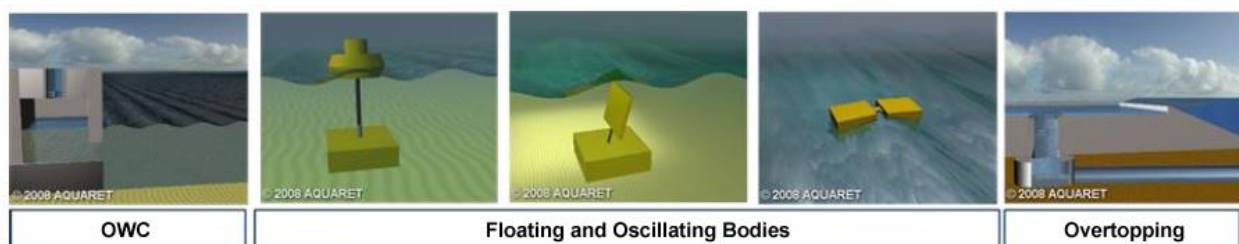


Figure 14 Main wave energy extraction systems

Source: adapted by author from (Brito e Melo, 2013).

Amongst the possible systems to utilize and for the physical conditions of the Costa Rican coastal lines, two technologies stand out, mainly the Pelamis Wave Energy Converter and the Aquamarine Oyster. The first being a floating body system and the second an oscillating body. Even though the Pelamis system has been tested for systems of over 4 MW and the Oyster has only reached 1 MW, the second system has been selected for the comparative analysis section of this study. The main reason for this is that while the company behind the Pelamis system collapsed and accumulated debts of over £15 million (Gourley, 2015), Aquamarine system was receiving funding from the European Commission through the EU Horizon 2020 program to further advance in their endeavor (Aquamarine Power, 2015).

The Aquamarine system is an Oscillating Wave Surge Converter (OWSC). These systems are especially adequate for shoreline and near shoreline areas (Aquamarine Power, 2015), which in term reduces transmission costs; an important limiting barrier for entrance of ocean energy systems. Typical deployment depth is between 10 and 15 m depths.

The oyster mechanism generates energy by transferring the resulting force of a wave against the wave energy converter (WEC) which in turn drives hydraulic pistons which pump pressurized

freshwater back to shore through a closed loop pipeline system (Figure 17). A hydroelectric plant onshore then converts the hydraulic pressure and flow into electrical power via a Pelton wheel turbine which drives electrical generators. (European Marine Energy Centre (EMEC), 2011)

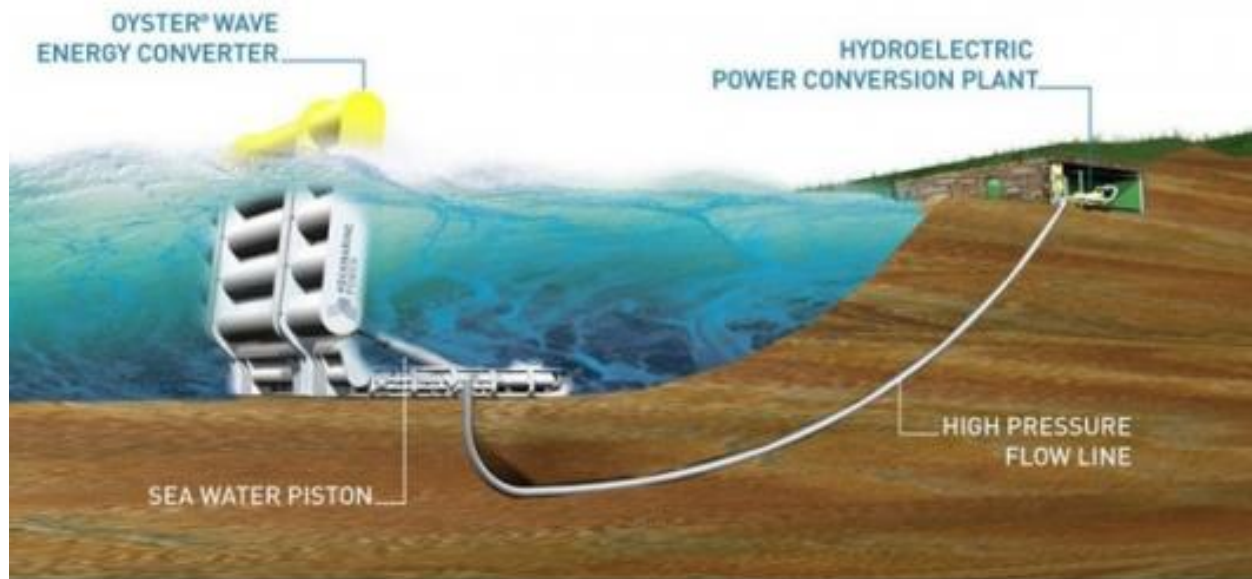


Figure 15 Oyster mechanism

Source: (Aquamarine Power, 2015).

Environmental impacts, although low, are identified mainly within the construction process and can be significantly mitigated with adequate planning. Maintenance can be done without the need of divers and might involve removal of isolated hydraulic modules, leak testing of pipelines, power-washing biofouling, and small areas of kelp removal or maintenance of any other component parts. (European Marine Energy Centre (EMEC), 2011)

Systems between 300 kW and 800 kW have been tested. Additionally, the organization won planning consent for a 40MW wave power site 500m off the west coast of Lewis, Scotland.² (Aquamarine Power, 2015)

² Since proposal of this study, the company was put up for sale, and ceased trading after this was not secured. Finally, Intellectual Property Rights were placed in the market after collapse of the organization. (Mackie, 2015)

4. COMPARATIVE ANALYSIS

Chapter four consists of a walkthrough of the process followed to conduct a comparative analysis through the calculation of Triple I Index (III): an analysis of currently present energy systems in Costa Rica in terms of Ecological Footprint, Cost Benefit analysis, and Social Impact survey results are presented. The aim of this chapter is to identify in environmental, economic and social terms which energy source has the least impact and highest climate change mitigation potential. Additionally, results for ocean energy in this evaluations are summarized and discussed.

4.1. SCENARIO DEFINITION

The methodology followed for the comparative analysis scenario is based on the study, further explained in sub title 4.5, by (Takahashi & Sato, 2015). In this study hydropower, coal, gas, wind, geothermal, biomass, solar PV, and wave energy systems are analyzed based on their Ecological Footprint (EF) , in terms of Cost Benefit (CB), and of end user preference of energy source in terms of social impact. Final results are compiled through the III for a net result in monetary terms of all aspects evaluated.

For the evaluation of the eight sources of energy all information utilized was to be comparable, being limited in that sense to the advances of wave energy. This study places a 10 MW limit on installed capacity as no ocean energy projects in near future are expected to surpass this barrier. Additionally, this limit falls within the accepted range for distributed generation systems. In terms of specific energy characteristics utilized for calculations of electricity generation, and emissions during production, the following factors were utilized:

Table 11 Emissions factors and efficiencies by source

Energy Source	Emissions Factor (t of CO _{2eq} / MWh)	Capacity Factor (Efficiency)
Hydropower	0.024	93%
Coal	0.325	85%
Gas	0.311	80%
Wind	0.007	38%
Geothermal	0.091	85%
Biomass	0.032	84%
Solar PV	0.050	21%
Wave	0.000	26%

Source: developed by author from: Emissions factors hydropower-wind-solar PV (Covenant of Mayors, 2010); coal-biomass (AVEBIOM, 2008), gas (Ministerio de Industria, Energía y Turismo, 2014),

geothermal (PROMOEENER-A, 2013); wave energy (IPCC, 2014). Capacity Factors: (Geothermal Energy Association, 2015).

Any variations on these factors will be specified in each subtitle when necessary. All calculations are designed estimating 340 operating days per year, working for 24 hours a day. A project lifespan of 20 years is utilized in the evaluations of EF and for CB analysis calculations, since the effect of discounting values beyond year 20 would not significantly affect the results. Although it is noted that most projects would continue operating after this period. S_{Impact} survey is based strictly on one year of energy generation, later converting end user preferences into Marginal Willingness to Pay and harmonizing to EF and CB. Based on the previously established conditions production per energy system was determined to be:

Table 12 Generation by energy source

Energy Source	Production (MWh/year)	Production (MWh/20 years)
Hydropower	75 888	1 517 760
Coal	69 360	1 387 200
Gas	65 280	1 305 600
Wind	31 008	620 160
Geothermal	69 360	1 387 200
Biomass	68 544	1 370 880
Solar PV	17 136	342 720
Wave	21 216	424 320

Source: developed by author.

Finally, as Costa Rica has a well-defined carbon market, under the tutelage of FONAFIFO, the following equivalency factor was utilized throughout the calculations:

Equation 5 Carbon emissions equivalency factor

$$5.05ha = 1 t \text{ of } CO_{2eq} = 1 \text{ Carbon Bond} = \$6 \text{ USD}^3$$

Source: Developed by author from (FONAFIFO, 2014) and (Castro R. , 1997).

³ By time of publication cost of a Carbon Bond had ascended to \$7.5, nevertheless the equivalency factor was kept at \$6 to maintain consistency with the data evaluated in Social Impact Survey. Future evaluations should update the equivalency factor.

4.2. ECOLOGICAL FOOTPRINT

“The Ecological Footprint measures the *supply of* and *demand on* nature. The supply, biocapacity, represents the planet’s biologically productive land areas including our forests, pastures, cropland and fisheries. These areas, especially if left unharvested, can also absorb much of the waste we generate, especially our carbon emissions.

Biocapacity can then be compared with humanity’s demand on nature: our Ecological Footprint. The Ecological Footprint represents the productive area required to provide the renewable resources humanity is using and to absorb its waste. The productive area currently occupied by human infrastructure is also included in this calculation, since built-up land is not available for resource regeneration. ” (The Global Footprint Network, 2015)

The basic Equation of for Ecological Footprint (EF) has been defined as follows:

Equation 6 Basic Ecological Footprint

$$EF = \frac{D}{Y}$$

Where:

D = demand of a product

Y = annual yield of the same product

Source: (Wackernagel & al, 2015).

In this study, as the aim is to determine impact of a specific energy towards the goal of Carbon Neutrality, carbon footprint of each individual source is estimated for the lifecycle considering carbon as the demand (D) and measured against forest carbon yield (Y) as carbon bonds in the nation are based on PES schemes developed from forest systems. According to National Forestry Law N° 7575 article 19, areas covered by forest will not be allowed to change their land use. Thus, any areas utilized for PES will maintain forest cover, making the use of forest carbon yield a consistent measure through time. In that sense (Castro R. , 1997) presented the capacity of absorption of the forest types present in Costa Rica as distributed in Holdridge life zones:

Table 13 Carbon absorption capacity of Costa Rican forests

Code	Type of Forest	t of CO ₂ sequestered per hectare per year (tons/ha/year)
Bh-T	Humid Tropical Forest	5.55
Bh-P	Humid pre-mountain forest	5.05
Bmh-T	Very humid tropical forest	6.36
Bmh-P	Very humid pre-mountain forest	5.93
Bmh-MB	Very humid low-lying mountain forest	4.35
Bp-P	Pre-mountain rain forest	5.04
Bp-MB	Low lying mountain rain forest	3.83
Bp-M	Mountain rain forest	2.85
Weighted Average		5.05

Source: reproduced by author from (Castro R. , 1997).

Lifecycle greenhouse gases identified for each source of energy together with the total production of energy measured in kWh provide us with an estimate of individual carbon demands.

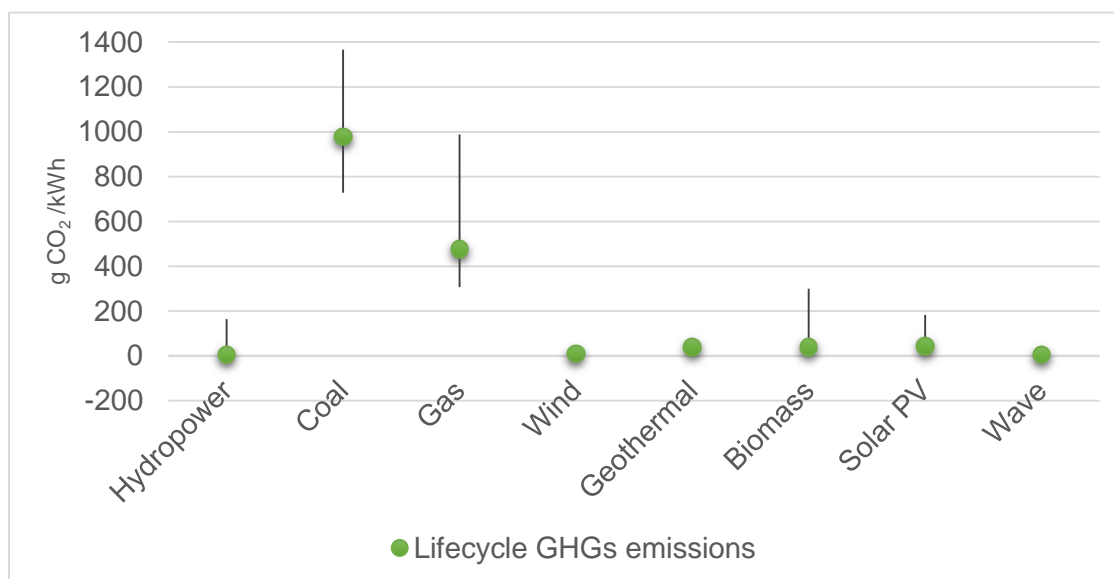


Figure 16 GHGs for lifecycle assessment of energy systems

Source: adapted by author from (OpenEI, 2015).

Figure 16 presents the Life Cycle Assessment (LCA) of each individual source of energy in terms of carbon, including max/min and median emissions, based on data published between 1970 and 2010. Included in the calculation are component manufacturing; operation of the generation facility to its decommissioning; and including acquisition, processing and transport of any required

fuels. (OpenEI, 2015) Additionally, in select technologies (coal, biomass, and wind) data was harmonized to adjust estimates in a way that they could be more methodologically comparable.

By converting g CO₂ / kWh to t CO₂ /kWh and utilizing total energy production of each source for the 20 year period, we get that:

Table 14 Project LCA Emissions

Energy Source	Project emissions (t of CO₂)
Hydropower	11 711
Coal	1 497 014
Gas	686 488
Wind	7 520
Geothermal	61 165
Biomass	60 445
Solar PV	16 622
Wave	3 742

Source: developed by author.

Emissions from fossil fuels are exponentially higher than those of any other renewable energy system. Amongst renewable energies geothermal and biomass systems are the largest emitters, however it should be noted that biomass can have significant variations depending on input material utilized. Emissions from hydropower, the nations preferred energy source are three times larger than those of wave energy.

By applying Equation 6 to the collected data, taking project emissions as demand (of tons of CO₂), and the forest area (in its capacity to sequester carbon) as our yield. We can estimate the amount of hectares required for projects to be carbon neutral. Figures 17 and 18 present an overview of the results.

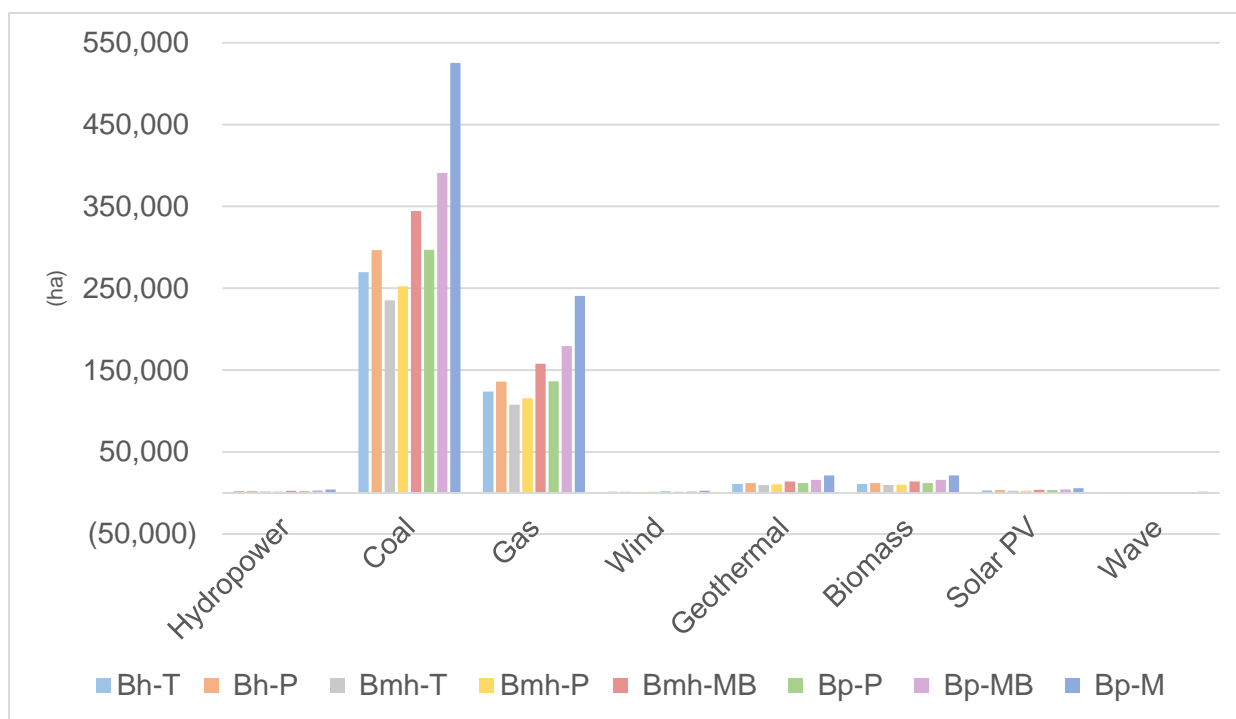


Figure 17 Forest area (ha) required to sequester project emissions by type of forest and energy source

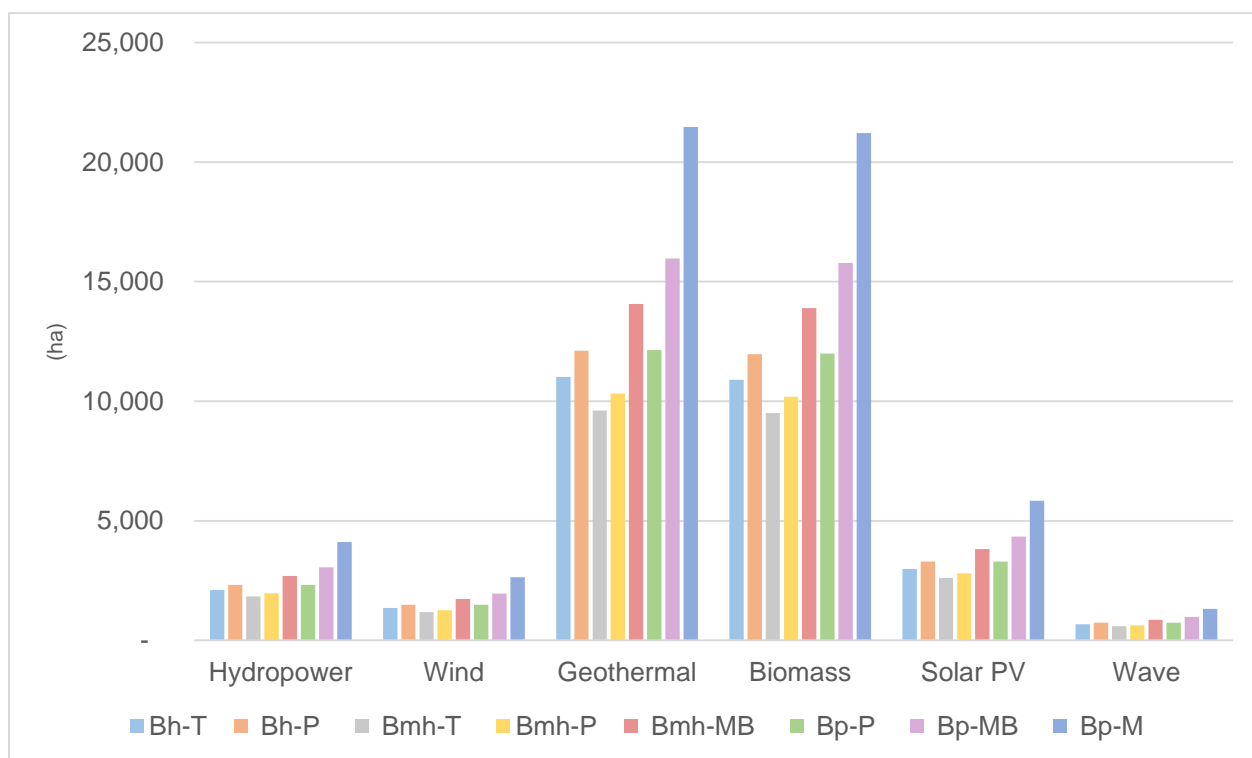


Figure 18 Forest area (ha) required to sequester project emissions by energy source and type of forest excluding coal and gas

Source: Figures 17 and 18 were developed by author.

Finally, utilizing the weighted average to estimate national average yield I calculated the EF of each individual energy source in terms of Costa Rican forest hectares as follows:

Table 15 Ecological Footprint of specific energy systems in terms of Costa Rican forest yield

	Ecological Footprint (Costa Rican ha)
Hydropower	2 319
Coal	296 438
Gas	135 938
Wind	1 489
Geothermal	12 112
Biomass	11 969
Solar PV	3 292
Wave	741

Source: developed by author.

4.3. COST BENEFIT ANALYSIS

For the Cost Benefit analysis, two scenarios were studied. In the first scenario, net present value (NPV) of each project is calculated utilizing current costs of energy production and initial investment; projects both self-financed and financed through a loan are compared.

In the second scenario, wave energy costs are adjusted based on the predicted change of investment costs presented in Table 12 and those of technology development. Additionally, in this scenario, wave energy subsidies are considered and we estimate how costs, subsidies and loans would have to behave for the project to break even or even generate profit.

Additionally from the characteristics described in subtitle 4.1, a set of basic assumptions were set as follows:

1. Projects are fixed at 10MW and no additional capacity is installed in response to growing demand.
2. Projects must be carbon neutral. Emissions above national average must be compensated, systems that produce less than national average can sell the excess in the carbon market.
3. Price per kWh is \$0.14 based on the average for the residential sector between 2009 and 2014, and has an annual growth rate of 2.68%.

4. Total produced energy is sold.
5. Initial investment cost for energy systems is:

Table 16 Initial investment costs

Energy Source	Investment Cost (\$/kW)	Total Initial Investment Cost (\$/10MW)
Hydropower	2 500	25 000 000
Coal	4 000	40 000 000
Gas	4 000	40 000 000
Wind	2 250	22 500 000
Geothermal	4 250	42 500 000
Biomass	700	7 000 000
Solar PV	2 750	27 500 000
Wave	3 500	35 000 000

Source: adapted by author from (CABEI, 2009).

6. Levelised cost of energy is utilized for production. This measure includes “capital costs, operating costs, cost of capital, capacity factor and generated electricity as well as the timing of all flows.” (Green Rhino Energy, 2015) Figure 19 presents the average costs utilized for this exercise as well as the range of costs for all sources:

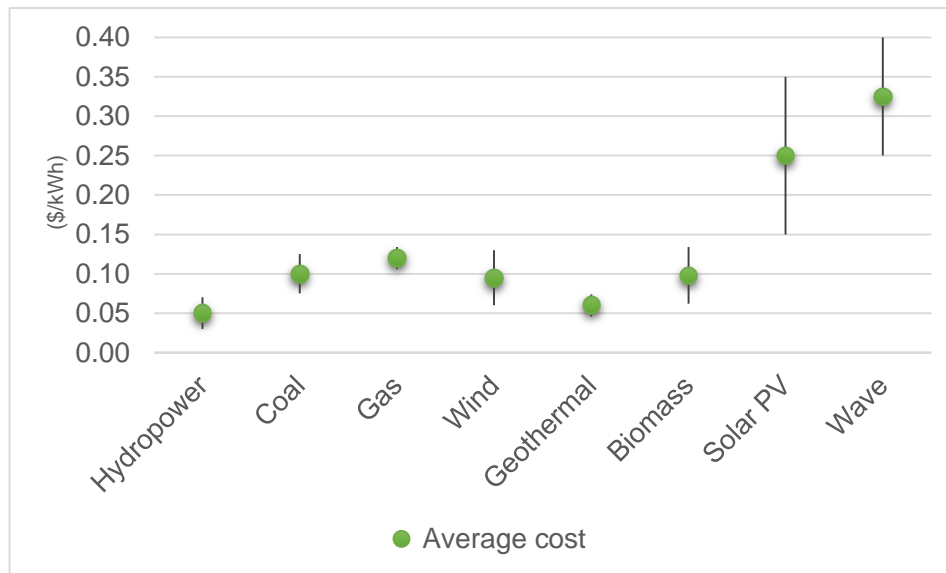


Figure 19 Levelised Cost of Energy

Source: adapted by author from (Green Rhino Energy, 2015).

7. When utilized, loan will cover 75% of initial investment and interest rate is set at 8.5%. The period of loan is 15 years.
8. Annual increase of costs is 2.5%.

9. Weighted average cost of capital is 7.46% utilized to calculate NPV of self-financed scenarios. Investor expected rate of return is 12% utilized to calculate NPV of financed through loan scenarios.
10. Income taxes are 30%.
11. No scale analysis was conducted given the lack of information on economies of scale.

4.3.1. FINANCED VS. NON-FINANCED

The first analysis provides the baseline for comparison, in the case for self-financed projects, the only options that result in a positive balance are hydropower, coal, and geothermal energy. Wind energy, is amongst remaining NTREs the closest to break even. Wave energy has the largest costs of any renewable energy, and benefit are second to last resulting in the largest loss.

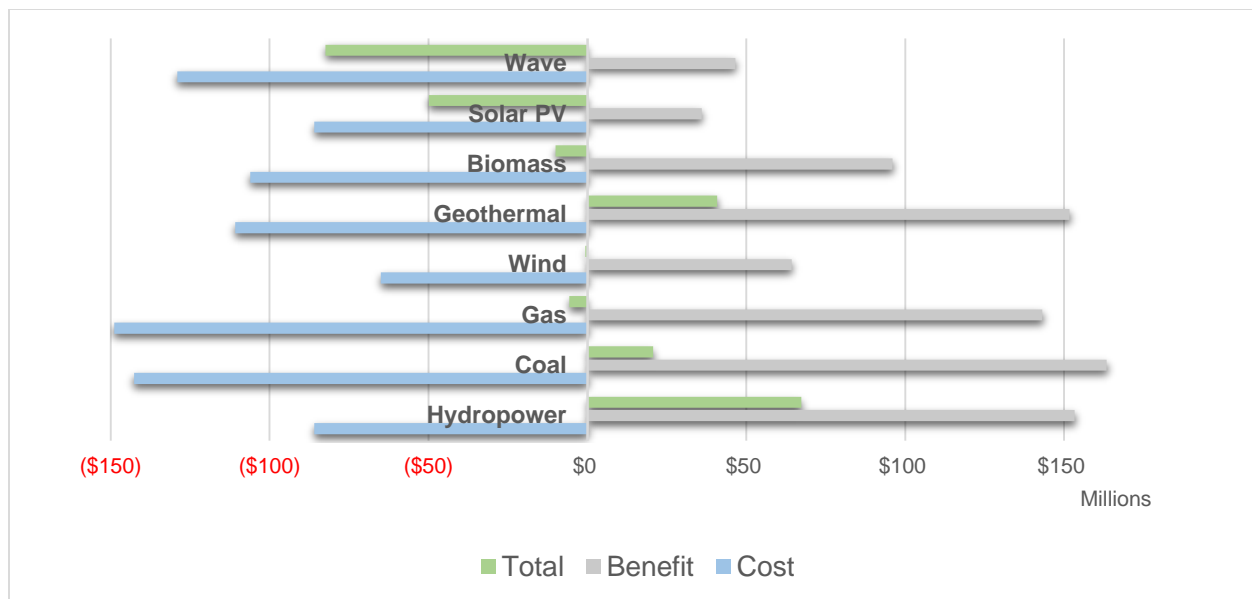


Figure 20 Cost Benefit analysis (self-financed)

Source: developed by author.

Figure 20 summarizes a more realistic scenario where access to loans is possible. In it, the effects on CB of diluting risk through support of a financial institution are visible. In general terms, total NPV tended to move closer to break-even point, making projects from biomass for example, more viable and reducing the impact of project failure in projects where cost is too high, such as wave and solar PV. However, those projects that were generating positive total benefit had a reduction in their balance, due to the financial cost. Hydroelectricity and geothermal energy maintain the

highest net benefit. This explains to some extent the fixation of national government and companies to increase production from these two sources. Scale of projects and inelastic production make reductions in marginal cost of production difficult.

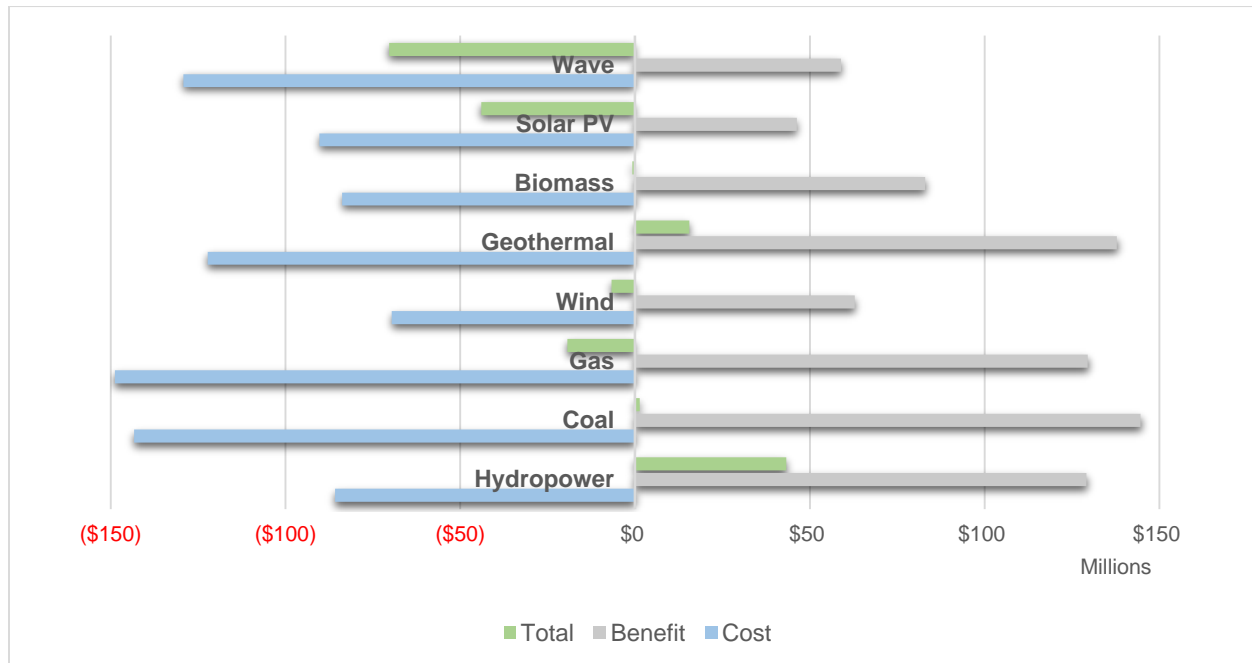


Figure 21 Cost Benefit analysis (financed through loan)

Source: developed by author.

4.3.2. ADJUSTED WAVE ENERGY

In the second scenario, wave energy was tested again, utilizing the lowest reported cost and applying an annual cost reduction of 5% due to technological advances based on (CABEI, 2009). In this scenario the study also analyzed variations of interest rate of loans and the introduction of a subsidy to cover initial investments. The aim of this exercise was to identify the mix of variables required for ocean energy to break-even or potentially generate profit.

The initial exercise, presented in Figure 22, consists of a subsidy of 25% of initial investment. Between loan and subsidy, full initial investment would be covered.

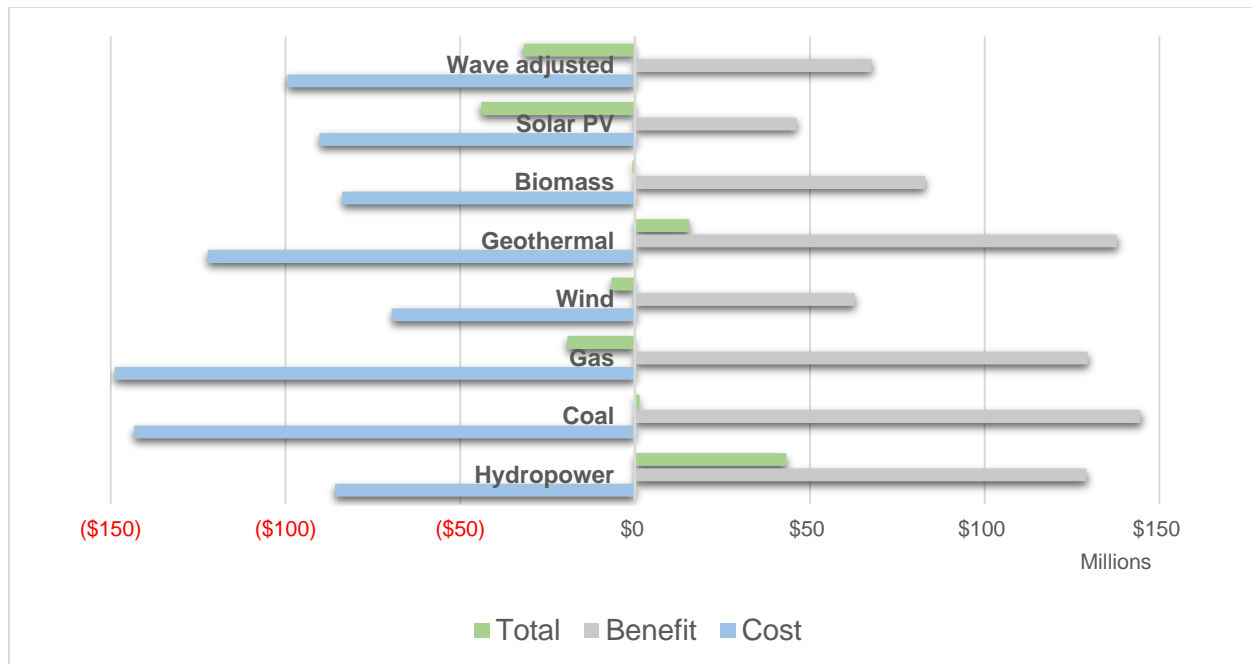


Figure 22 Cost Benefit analysis with adjusted costs for wave energy

Source: developed by author.

Although wave energy presents a better net result than that of solar PV, it is still insufficient to break even. Cost at this stage are still prohibitive for the introduction of ocean energy systems in Costa Rica, and price variations would not be sufficient to cover for the gap produced.

Considering the interest of the country to study the viability of ocean energy systems in Costa Rica, and the possibility to subsidize the generation in the aim to achieve SE4ALL even at a high cost; the study set out to determine three what-if scenarios to study effects of possible changes in:

- interest loan rates and cost reduction from technology development (Table 17),
- changes in subsidy and cost reduction from technology development in systems financed with a loan (Table 18), and
- subsidies and cost reduction from technology development in self-financed systems (Table 19).

Second and third exercises aim to find the values in the variables that could produce a break-even scenario in terms of net NPV. The first scenario shows that ocean energy is not viable from a CB perspective under all variations tested. The optimum case of a 5% interest rate and a 25%

annual reduction in cost from energy development still resulted in a negative total NPV with losses of over \$ 6 million USD.

Table 17 What if analysis: Interest rate and adjusted cost

		Adjusted cost from technology development				
INTEREST ON LOAN	%	-5%	-10%	-15%	-20%	-25%
	5.0%	-25 612 255	-17 666 153	-12 499 964	-8 937 376	-6 362 763
	5.5%	-26 442 635	-18 476 912	-13 292 878	-9 719 639	-7 132 534
	6.0%	-27 288 782	-19 307 851	-14 105 518	-10 516 300	-7 916 485
	6.5%	-28 150 643	-20 153 957	-14 937 055	-11 330 073	-8 724 517
	7.0%	-29 030 526	-21 015 171	-15 783 316	-12 166 693	-9 549 837
	7.5%	-29 927 548	-21 891 850	-16 644 239	-13 017 770	-10 389 405
	8.0%	-30 840 245	-22 788 998	-17 523 689	-13 883 236	-11 243 155
	8.5%	-31 768 536	-23 701 198	-18 422 447	-14 763 586	-12 114 059
	9.0%	-32 712 333	-24 628 360	-19 335 826	-15 668 049	-13 008 078
	9.5%	-33 671 546	-25 570 392	-20 263 737	-16 586 857	-13 916 250
	10.0%	-34 646 074	-26 531 201	-21 209 984	-17 519 918	-14 838 484

Source: developed by author.

When utilizing a loan, the project would not be viable in any scenario if annual cost reduction is set at 5%. With a 10% annual reduction a subsidy of 95% would be required, with a 15% reduction a subsidy of 80% would be required, and so on. The lowest possible subsidy, at 60% would require costs to reduce 25% annually. At the time, none of these scenarios seem realistic.

Table 18 What if analysis: Subsidy and adjusted cost with a loan

		Adjusted cost from technology development				
SUBSIDY	%	-5%	-10%	-15%	-20%	-25%
	10%	-37 018 536	-28 951 198	-23 672 447	-20 013 586	-17 364 059
	15%	-35 268 536	-27 201 198	-21 922 447	-18 263 586	-15 614 059
	20%	-33 518 536	-25 451 198	-20 172 447	-16 513 586	-13 864 059
	25%	-31 768 536	-23 701 198	-18 422 447	-14 763 586	-12 114 059
	30%	-30 018 536	-21 951 198	-16 672 447	-13 013 586	-10 364 059
	35%	-28 268 536	-20 201 198	-14 922 447	-11 263 586	-8 614 059
	40%	-26 518 536	-18 451 198	-13 172 447	-9 513 586	-6 864 059
	45%	-24 768 536	-16 701 198	-11 422 447	-7 763 586	-5 114 059
	50%	-23 018 536	-14 951 198	-9 672 447	-6 013 586	-3 364 059
	55%	-21 268 536	-13 201 198	-7 922 447	-4 263 586	-1 614 059
	60%	-19 518 536	-11 451 198	-6 172 447	-2 513 586	135 941
	65%	-17 768 536	-9 701 198	-4 422 447	-763 586	1 885 941
	70%	-16 018 536	-7 951 198	-2 672 447	986 414	3 635 941
	75%	-14 268 536	-6 201 198	-922 447	2 736 414	5 385 941
	80%	-12 518 536	-4 451 198	827 553	4 486 414	7 135 941
	85%	-10 768 536	-2 701 198	2 577 553	6 236 414	8 885 941
	90%	-9 018 536	-951 198	4 327 553	7 986 414	10 635 941
	95%	-7 268 536	798 802	6 077 553	9 736 414	12 385 941
	100%	-5 518 536	2 548 802	7 827 553	11 486 414	14 135 941

Source: developed by author.

The scenario without any loan presented the most possibilities for project to be viable. In this case project could be viable if a reduction in annual costs of 10% was achieved and an 80% subsidy is attained.

Table 19 What if analysis: Subsidy and adjusted cost with no loan

		Adjusted cost from technology development				
	%	-5%	-10%	-15%	-20%	-25%
SUBSIDY	10%	-35 084 198	-23 254 187	-15 929 118	-11 094 385	-7 737 167
	15%	-33 334 198	-21 504 187	-14 179 118	-9 344 385	-5 987 167
	20%	-31 584 198	-19 754 187	-12 429 118	-7 594 385	-4 237 167
	25%	-29 834 198	-18 004 187	-10 679 118	-5 844 385	-2 487 167
	30%	-28 084 198	-16 254 187	-8 929 118	-4 094 385	-737 167
	35%	-26 334 198	-14 504 187	-7 179 118	-2 344 385	1 012 833
	40%	-24 584 198	-12 754 187	-5 429 118	-594 385	2 762 833
	45%	-22 834 198	-11 004 187	-3 679 118	1 155 615	4 512 833
	50%	-21 084 198	-9 254 187	-1 929 118	2 905 615	6 262 833
	55%	-19 334 198	-7 504 187	-179 118	4 655 615	8 012 833
	60%	-17 584 198	-5 754 187	1 570 882	6 405 615	9 762 833
	65%	-15 834 198	-4 004 187	3 320 882	8 155 615	11 512 833
	70%	-14 084 198	-2 254 187	5 070 882	9 905 615	13 262 833
	75%	-12 334 198	-504 187	6 820 882	11 655 615	15 012 833
	80%	-10 584 198	1 245 813	8 570 882	13 405 615	16 762 833
	85%	-8 834 198	2 995 813	10 320 882	15 155 615	18 512 833
	90%	-7 084 198	4 745 813	12 070 882	16 905 615	20 262 833
	95%	-5 334 198	6 495 813	13 820 882	18 655 615	22 012 833
	100%	-3 584 198	8 245 813	15 570 882	20 405 615	23 762 833

Source: developed by author.

The testing of these scenarios provides relevant insights for the future analysis of ocean energies in Costa Rica. First of all, if prices follow the average annual growth of the past five years, any wave energy system would require important subsidies to be viable. Public or private projects that would not require a loan tend to be more viable, however, in case of failure the loss could potentially be in the magnitude of \$ 35 million USD. Even if the most cost efficient technology currently available in the market is utilized, important subsidies would have to go into place for project to be viable.

We can conclude from this exercise that wave energy, from a cost benefit perspective, is not a viable option in the near future for Costa Rica, but could hypothetically be so in the future. Further studies should be conducted to evaluate feasibility with economies of scale when data becomes available.

4.4. SOCIAL IMPACT

4.4.1. CONJOINT ANALYSIS

Conjoint analysis was utilized to evaluate public acceptance of energy sources based on specific social impacts and predict acceptance of wave energy, as well as to determine preferred energy sources in the context of attaining Carbon Neutrality and SE4ALL. “Conjoint or trade-off analysis has become one of today’s most commonly used market research tools for designing and pricing products and services.” (Orme, 2014)

The conjoint analysis model selected is Choice Based Conjoint (CBC), this model allows to mimic the process a consumer follows in the selection of a product they will purchase, including the possibility of no purchase occurring. Results however are presented in terms of market share of products when a purchase occurs.

Instead of exclusively evaluating each attribute a product may have individually, the Hierarchical Bayes model is utilized to evaluate respondents’ preferences in two levels. Individual part worths described through multivariate normal distribution, and the model followed to select a specific technology based on the identified betas of initial stage (usually multinomial logit or linear regression). (Orme, 2000) This allows market segmentation to be more adequately determined and thus understand population weighted averages and individual results for specific demographic groups.

Furthermore, as stated by Takahashi and Sato, “Conjoint analysis allows for the cost to be calculated for each attribute of the evaluation target by repeatedly asking respondents about their preference with respect to multiple evaluation targets.” (Takahashi & Sato, 2015)

Each energy source is evaluated in terms of specific attributes described in the following subtitle and evaluated by respondents. The results allow us to determine weight of importance of each attribute in the selection of an energy source, predicted utilities of energy sources based on each respondent preference or rejection of a specific attribute, and finally simulate a market to determine expected selection of energy source based on the results of the first two stages.

The utilization of conjoint analysis in this way allows to later determine the Marginal Willingness to Pay (MWTP) of each attribute and thus determine in monetary terms the public preference of an energy source in respect to social impacts.

The survey was designed utilizing licensed Sawtooth Software (SSI Web Version 8_4_8_1), and conducted via web by respondents in Costa Rica.

4.4.2. ENERGY SOURCE ATTRIBUTES TESTED

For the development of the CBC Analysis, each product (energy source) was defined in terms of its social impacts in relation to the two SDGs discussed as main goals. In this sense, the study intended to determine amongst the selected energy sources, which would be preferred by end users if they could select the source that supplies their energy, for what reasons, and how much would they be willing to accept or reject a specific impact generated by energy production.

As such, the eight energy sources studied throughout the previous titles were compared in relation to their cost, their capacity to generate electricity in terms of amount of families that would be covered by production, changes in CO₂ emissions over national average, area of impact based on the amount of hectares required to sequester the carbon produced, and the cost of carbon sequestration. Finally, hydrological footprint was utilized to evaluate the relevance respondents would place on stressing of water resources. Sample questions of CBC study are available in APPENDIX 1.

In that sense the following data was utilized:

1. Cost: median value in Figure 19 was utilized.
2. Coverage: energy production per month of each source is measured based on the scenario definition in title 4.1. Production is converted to amount of families covered by production considering an average family in Costa Rica consists of four members and monthly consumption is of 200 kWh based on ICE annual statistics.
3. Changes in CO₂ emissions: emissions of each energy source are calculated based on the scenario defined in title 4.1. National average emission factor is set at 0.13 t of CO₂eq per MWh based on (IMN, 2014). Finally, Equation 1 was utilized to measure changes over national average.
4. Area: carbon emissions for one year of production were calculated based on the scenario defined in title 4.1. Emissions are divided by weighted average absorption of forest in Table 13.
5. Cost of carbon sequestration: carbon emissions for one year of production were calculated based on the scenario defined in title 4.1. Cost of carbon sequestration is established in Equation 5.
6. Hydrological footprint: water footprint was established according to Table 20. Wave energy is assumed to have the same HF factor as hydropower because the oyster mechanism utilizes the same type of energy conversion system on land.

Table 20 Water footprint of energy sources

Energy Source	HF Factor (l / kWh)
Hydropower	7.57
Coal	3.20
Gas	1.21
Wind	0.00
Geothermal	15.14
Biomass	1.89
Solar PV	3.18
Wave	7.57

Source: developed by author with data from (Argonne National Laboratory, 2011).

Therefore, products were defined in terms of their specific attributes, as established in Table 21. Nevertheless, after initial testing of questionnaire, respondents considered this to be too much data and too difficult to follow, especially for those that did not understand what some of the attributes represented in regards to other energy systems. Therefore a simple hierarchy matrix was established specifically for the scenarios being evaluated (APPENDIX 2). An additional website was created utilizing google pages to provide instructions for respondents and for them to have access to the matrix throughout the questionnaire.

Table 21 Attributes of energy sources

	Cost	Families covered	CO ₂ Changes over national Average	Area	Cost of Sequestration	Hydrological Footprint
	\$ / kWh			ha		l / year
Hydropower	\$ 0.050	31 620	- 8 787	361	\$ 10 928	574 534
Coal	\$ 0.100	28 900	11 964	4 470	\$ 135 431	221 860
Gas	\$ 0.120	27 200	9 694	4 020	\$ 121 812	79 076
Wind	\$ 0.095	12 920	- 10 391	43	\$ 1 302	0
Geothermal	\$ 0.060	28 900	- 4 296	1 250	\$ 37 871	1 050 224
Biomass	\$ 0.098	28 560	- 8 421	433	\$ 13 123	129 734
Solar PV	\$ 0.250	7 140	- 9 751	170	\$ 5 141	54 488
Wave	\$ 0.325	8 840	10 608	0	\$ 0	160 623

Source: developed by author.

4.4.3. SURVEY RESULTS

A total of 1 027 people participated in the survey, of which 153 people completed the total. The complete demographic composition of the survey is presented in APPENDIX 3. Results have been divided in three main areas, importance given to each individual attribute, predicted utilities of individual attributes, and market simulation based on previous two results. Importance and market simulation are presented in the following subtitles, while utilities are discussed with MWTP.

4.4.3.1. *Importance of attribute*

The first Figure in this section summarizes total results of survey. As expected, cost was the most relevant attribute of an energy system selected by the respondents. The second most relevant attribute, given a weight of 20.81%, is the hydrological footprint, changes in CO₂ is the third most relevant weight. The least relevant attribute is coverage, this value could be due to accessibility to the service being considered satisfactory by a majority of the population or because of high concentration of respondents in the Great Metropolitan Area (GAM) where access is not an issue; an increase in respondents from the rural areas is expected to vary results. Limitations in term of access to internet service in communities with no electric service is small, but would also have an impact on the weight of this attribute.

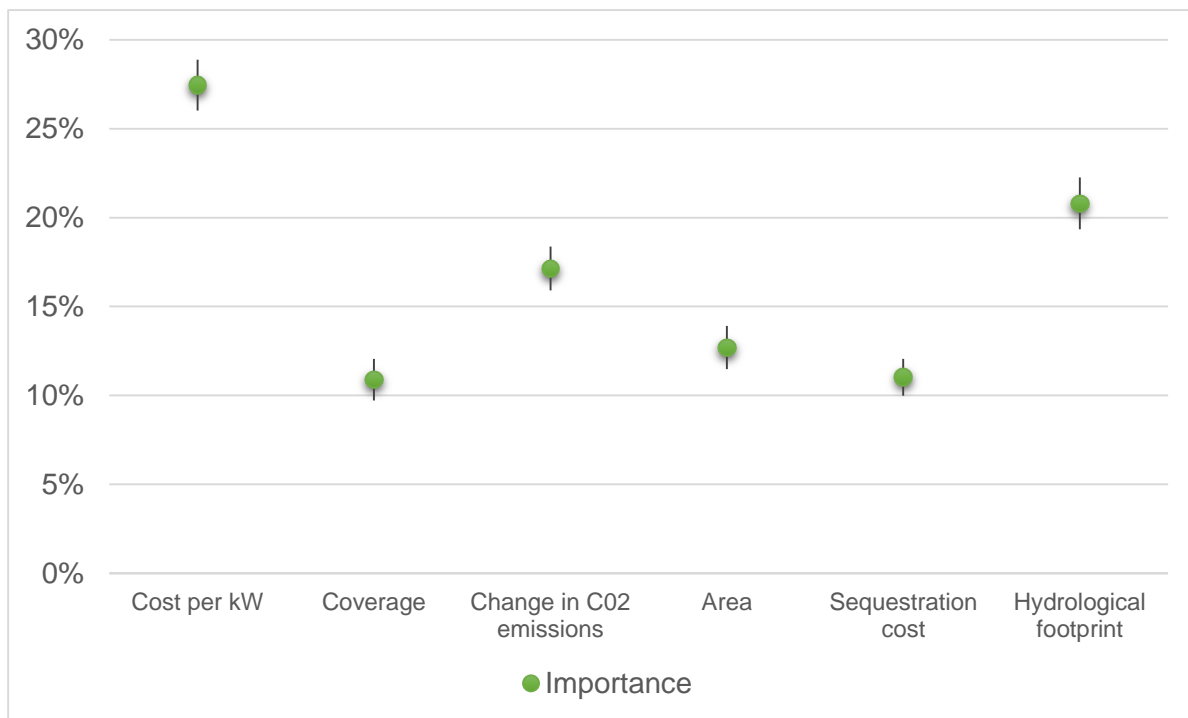


Figure 23 Importance of individual assets (including max/min and median)

Source: developed by author.

When analyzing results in regards to age, cost is the most relevant value amongst all groups except for those between 65 and 74 who valued hydrological footprint slightly higher. Coverage is most important to the group between 55 and 64. Changes in CO₂ emissions is most significant amongst those aged 18 to 24. Area required for sequestration and cost of sequestration are most relevant to the groups between 25 and 34, and 65 to 74 respectively.

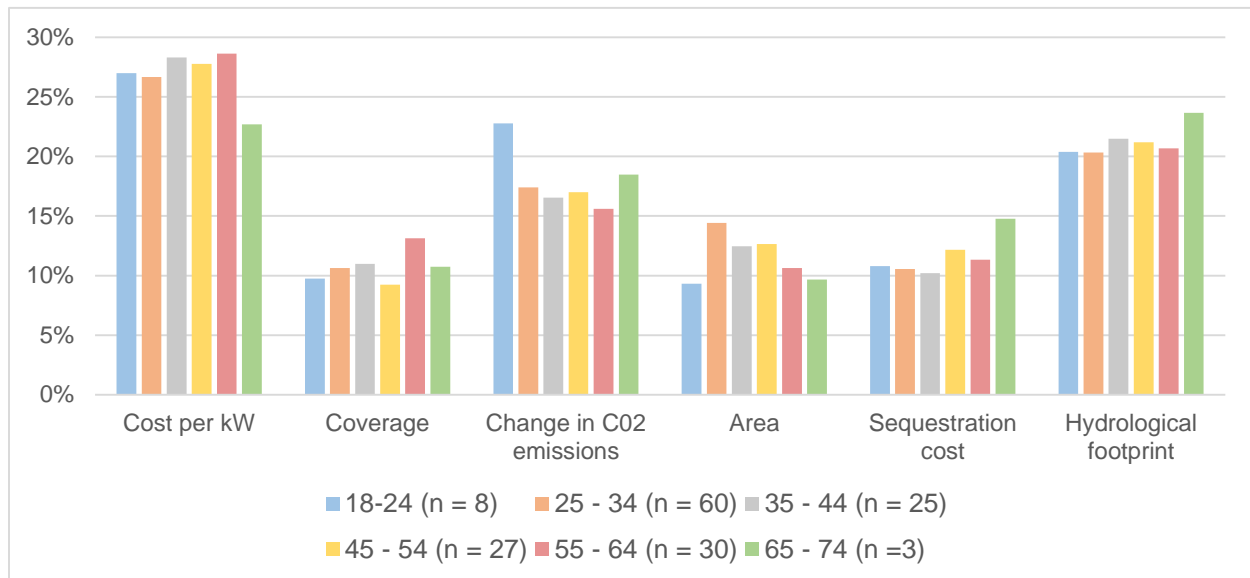


Figure 24 Importance of individual attributes by age groups

Source: developed by author.

Cost and coverage are slightly more relevant to men, while hydrological footprint, area of sequestration and changes in emissions are more important to women.

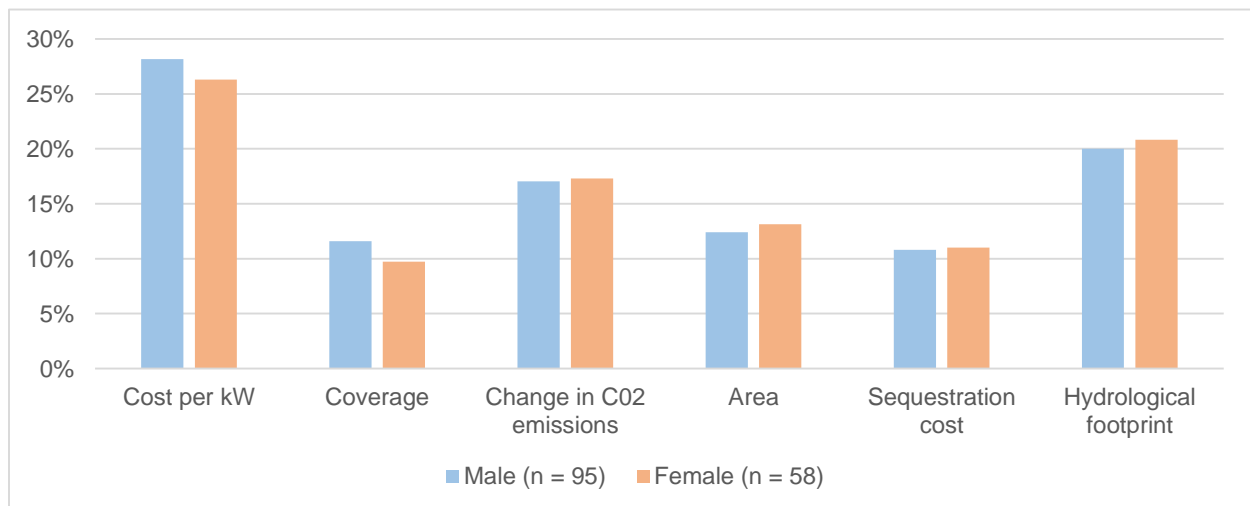


Figure 25 Importance of individual attributes by sex

Source: developed by author.

In terms of education level, cost is most relevant to those with a technical or vocational degree, and least to those that have not finalized college education. Respondents with a doctoral degree considered coverage, changes in emissions and hydrological footprint almost equally. Those with a master's degree cared least about coverage and cost of sequestration.

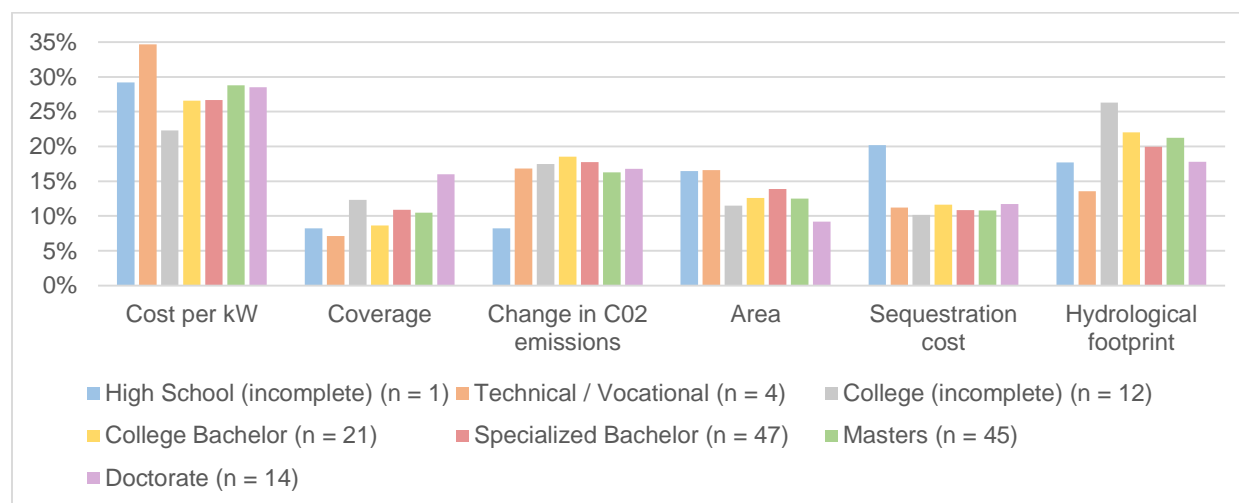


Figure 26 Importance of individual attributes by highest level of education obtained

Source: developed by author.

Cost was most relevant to the respondents from Cartago, while they were least interested in the hydrological footprint. The respondent from Guanacaste (in the North Pacific Region prone to droughts) focused strongly on hydrological footprint, nevertheless, further studies should be conducted to reduce the urban-bias and acquire more results from rural areas.

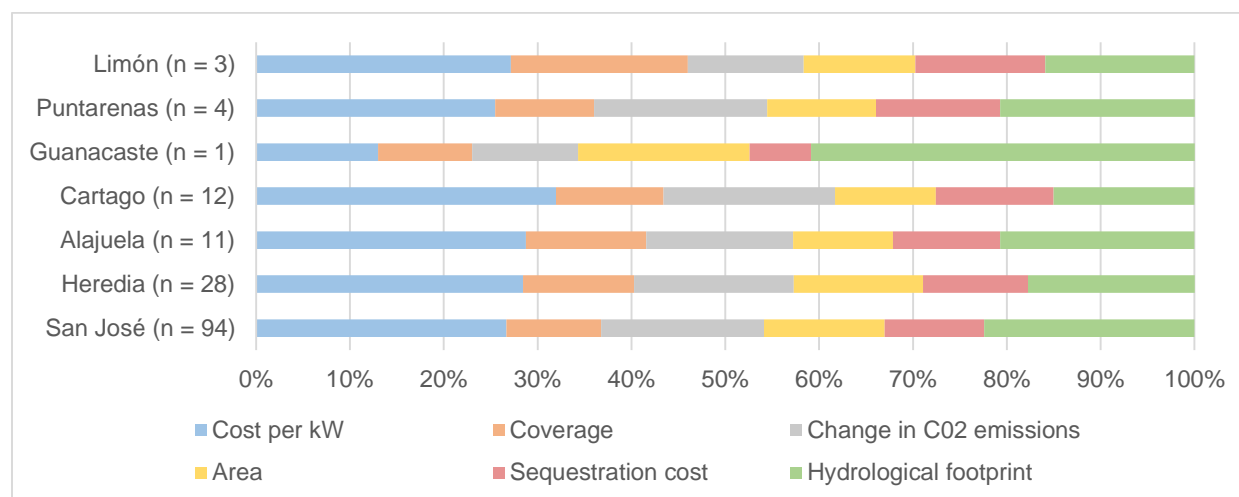


Figure 27 Importance of individual attributes by province in which they live

Source: developed by author.

Based on employment status and sector, those unemployed cared most about hydrological footprint and least about cost. Students gave a larger weight to changes in emissions than any other group. While those in academia valued hydrological footprint the highest after cost. Respondents employed in the NGO sector were the group that provided the highest importance to cost, however, sequestration cost was the lowest in their scale.

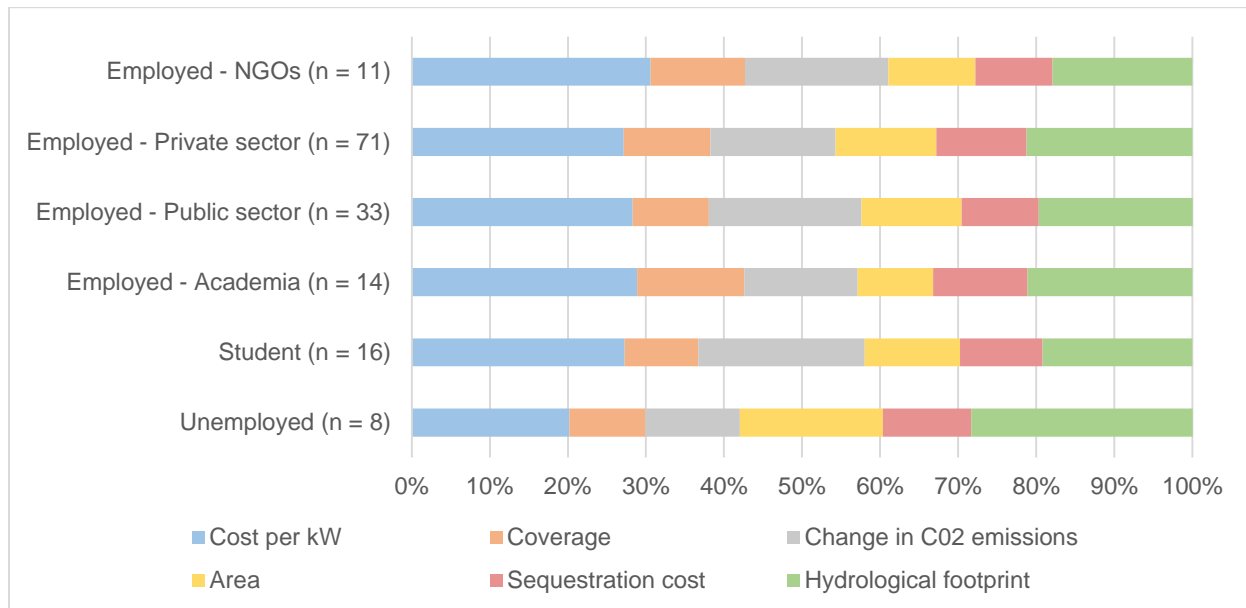


Figure 28 Importance of individual attributes by status of employment and sector

Source: developed by author.

Final Figure presents results based on respondent's originally claimed preference. Amongst all respondents those who selected geothermal energy gave the most relevance to cost, while those that selected gas weighed it the least high; both gave the highest values to coverage. In terms of changes in emissions, those that selected other, biomass and none valued it the highest, while gas and wave weighed it the lowest.

Area required for sequestration was weighed the highest for those who selected hydroelectricity and wave energy. Cost of sequestration was most important for those that selected gas, followed by wave and other. Finally, hydrological footprint was the least relevant for those that had selected geothermal, followed by solar and other; it was most highly weighed by those who selected wind and biomass.

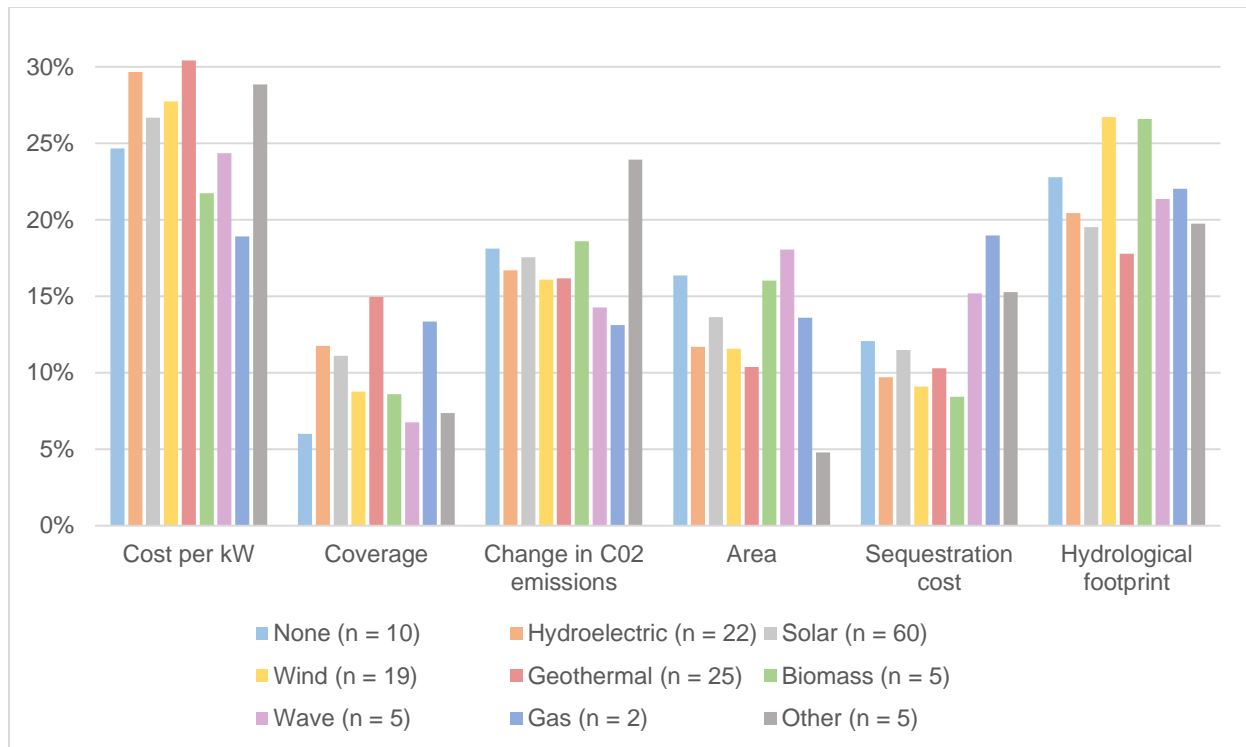


Figure 29 Importance of individual attributes by theoretically preferred energy source

Source: developed by author.

4.4.3.2. Market simulation

Market simulation analysis is conducted utilizing the pre-defined products, in this case the energy sources and their specific attributes as presented in title 4.4.2. In this evaluation the study presents what energy systems would be selected by respondents within the options available to them in the market generated through our initial scenario. Energy preference is defined through market share in this exercise.

Additionally, utilizing respondents' originally claimed preference the study is able to identify differences between respondent perceived preferences and actual preference based on the attributes evaluated. This exercise provides interesting inputs in the aim to increase public knowledge of energy systems and understand gaps in public acceptance.

In general terms, taking into consideration the average weight placed by respondents to each attribute and the composition of each energy source, the study found that 45.18% of times wind energy would be the selected source. Biomass would be selected in the market 20.90% of times

making it the second most preferred energy source, followed by hydroelectricity being selected 12.88% of times.

No other energy source resulted as selected over 10% of times from the simulation, while coal would be the least preferred source in the marketplace being selected only 2.24% of times when a purchase is completed. Wave energy would be selected 4.37% of times making it the third least selected energy source.

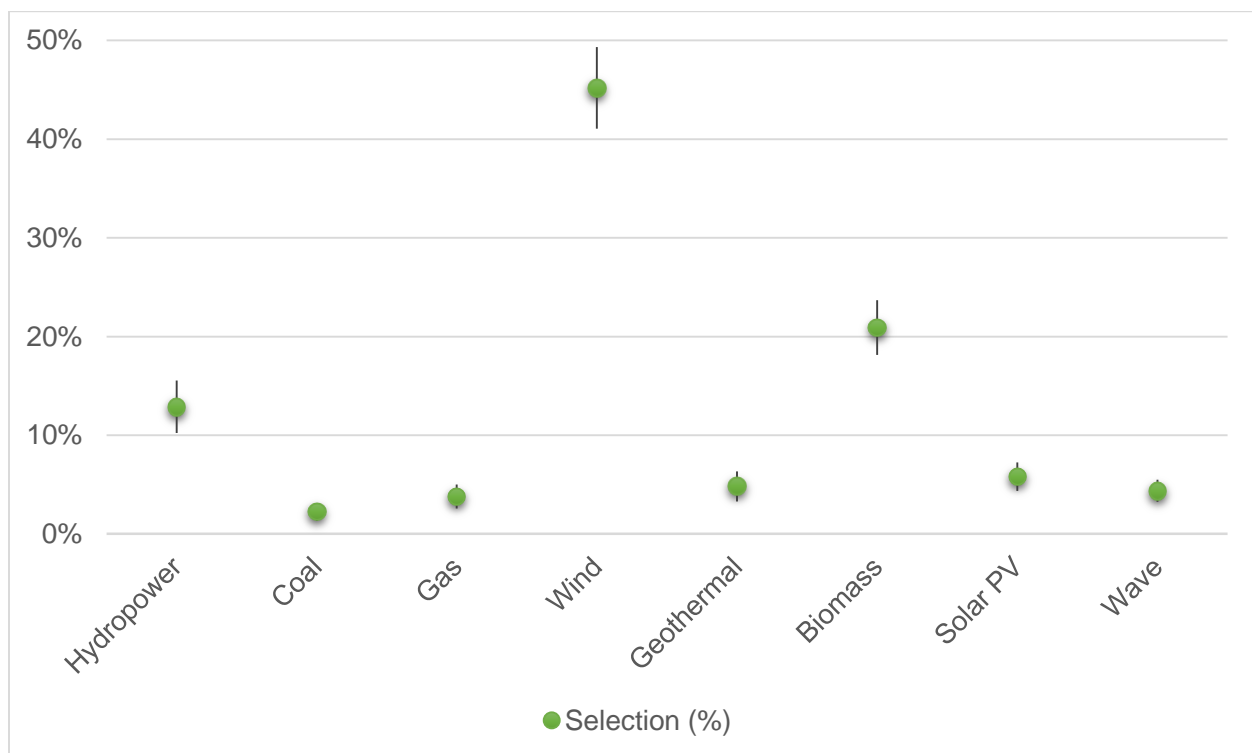


Figure 30 Energy source selection in market simulator (including max/min and median)

Source: developed by author.

Public preference of wind energy must be further analyzed taking into consideration possible NIMBY effect on acceptance, as wind turbines are many times rejected based on their visual effects to the landscape.

In terms of energy source preference, wind is significantly more preferred by women, while men have noticeably higher preferences than women over hydropower and biomass.

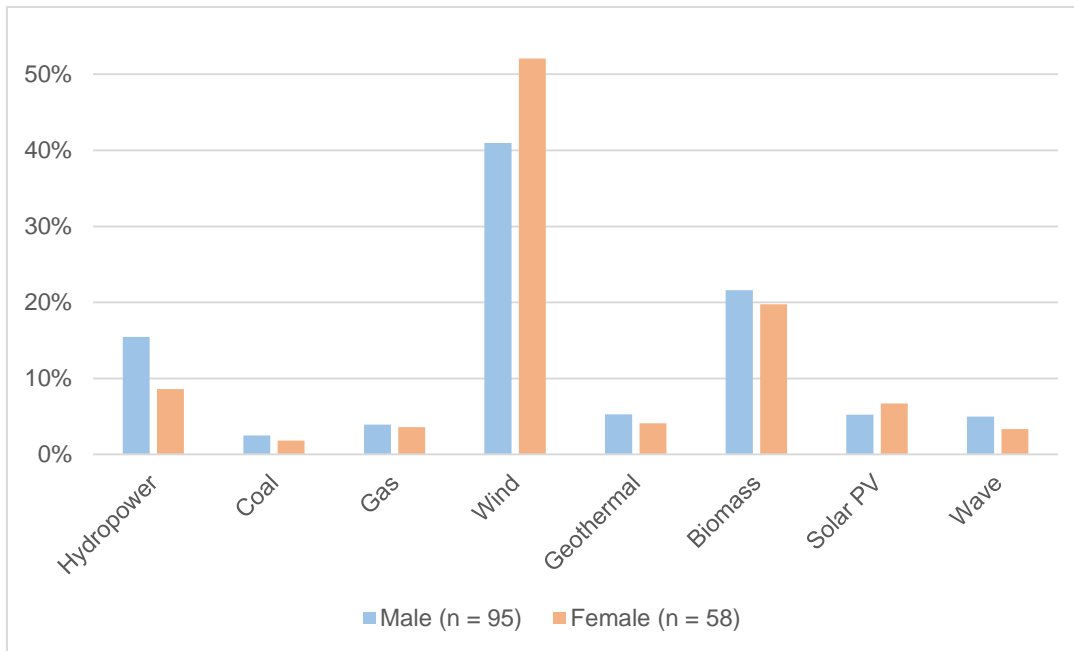


Figure 31 Energy source selection in market simulator by sex

Source: developed by author.

Amongst age groups, wind energy would be the most selected energy source by all age groups except those between 18 and 24, who have a noticeable preference for biomass, selecting it over 36% of times.

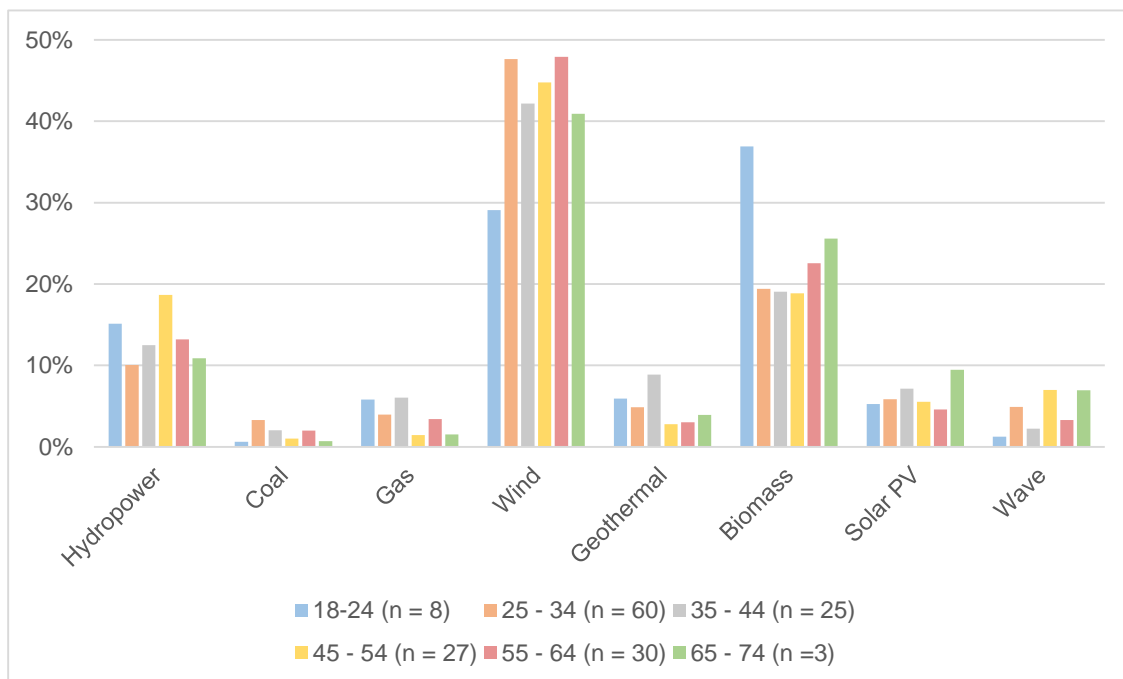


Figure 32 Energy source selection in market simulator by sex

Source: developed by author.

In terms of highest level of education attained, wind energy would be selected the most amongst those who hold a master's degree, followed by respondents that have completed a college bachelor. Respondents with a doctoral degree are consistent with total averages and would select wind energy, hydropower and biomass more times than any other energy source. Nevertheless, hydropower would be second in their hierarchy over biomass.

Solar energy would be most selected amongst those respondents with lower levels of education, however, further studies should be developed to further elucidate on their preference as current population of lower end respondents is significantly smaller than those with higher educational degrees.

Wave energy, would most likely be selected by those holding a technical or vocational degree, and those with incomplete college, and would be least selected by those that have not completed high school followed by those that hold a bachelor's degree.

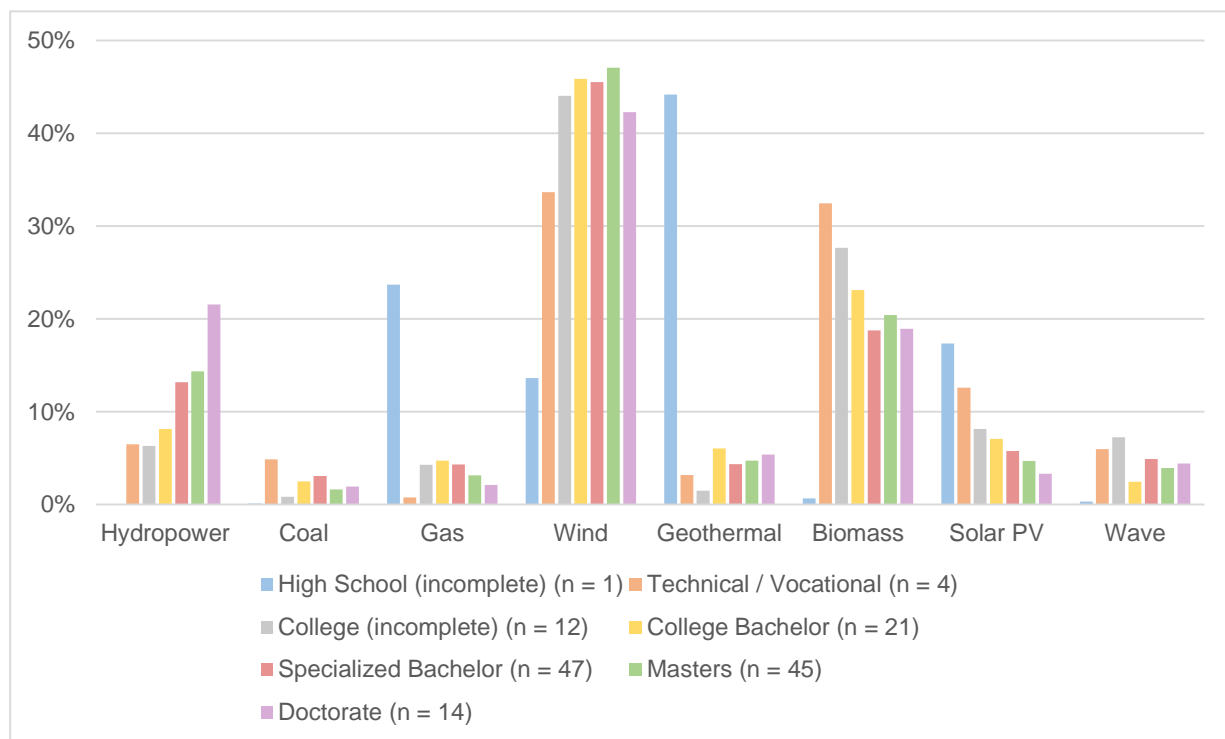


Figure 33 Energy source selection in market simulator by highest level of education

Source: developed by author.

Hydropower would be selected the most times by residents of Heredia and Cartago. Solar PV would most be selected amongst those that reside in San José and Puntarenas. Biomass on the other hand, is strongly preferred by inhabitants of Limón, the only group not to select wind above any other source. Wind energy in turn, would be the most selected source with particularly high market shares in Guanacaste, San José and Alajuela.

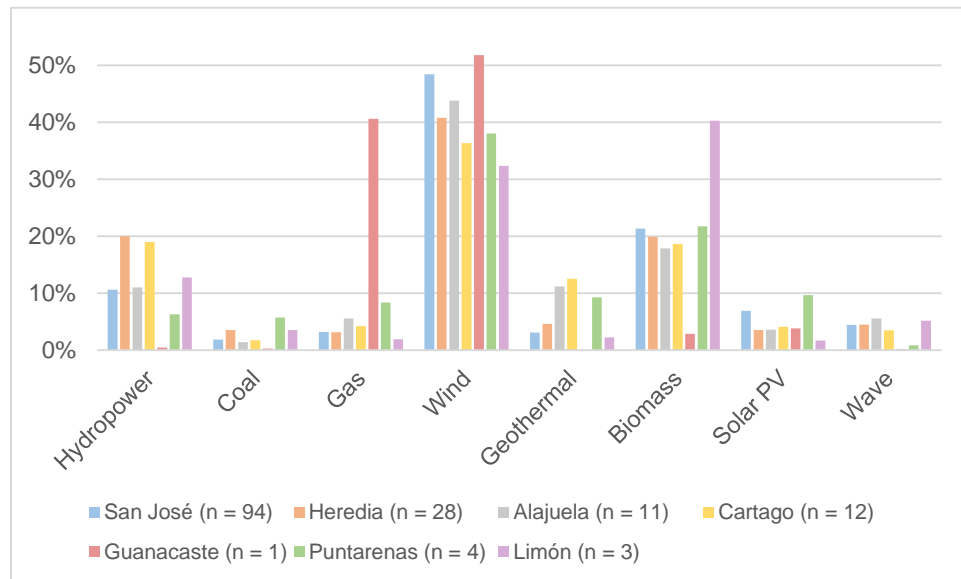


Figure 34 Energy source selection in market simulator by province in which they live
Source: developed by author.

In terms of employment and sector, public employees would most likely select wind energy followed by the private sector, academic sector would be the least likely.

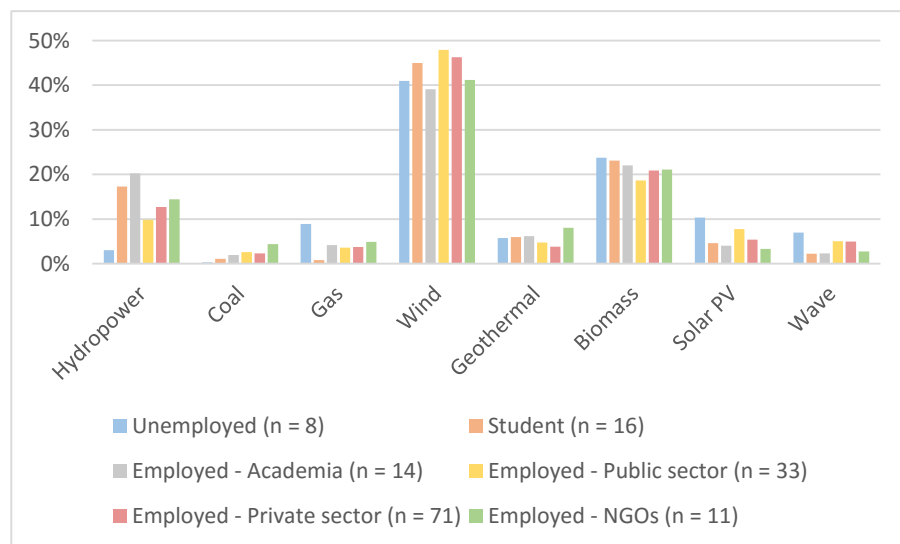


Figure 35 Energy source selection in market simulator by province in which they live
Source: developed by author.

Finally, amongst those respondents that considered themselves as having no preferred energy source 58.33% of times would select wind energy. Similarly, those who considered wave energy to be their preferred source, would select 57.59% of times. Respondents who claimed to prefer hydroelectricity, would only select it 17.82% of times, making them the second most likely group to select the source after respondents who considered their preference to be geothermal energy.

Those respondents that considered gas or biomass to be their preferred source where the only groups to maintain relative consistency, being the largest within their final selection. Yet, respondents who claimed to prefer gas would select wind energy and geothermal energy more times than gas. Those who claimed to prefer biomass would select wind energy slightly more often than biomass.

Wave energy would most likely be selected by those who claimed to prefer gas and wind, and least by those who considered their preference to be biomass or hydroelectricity.

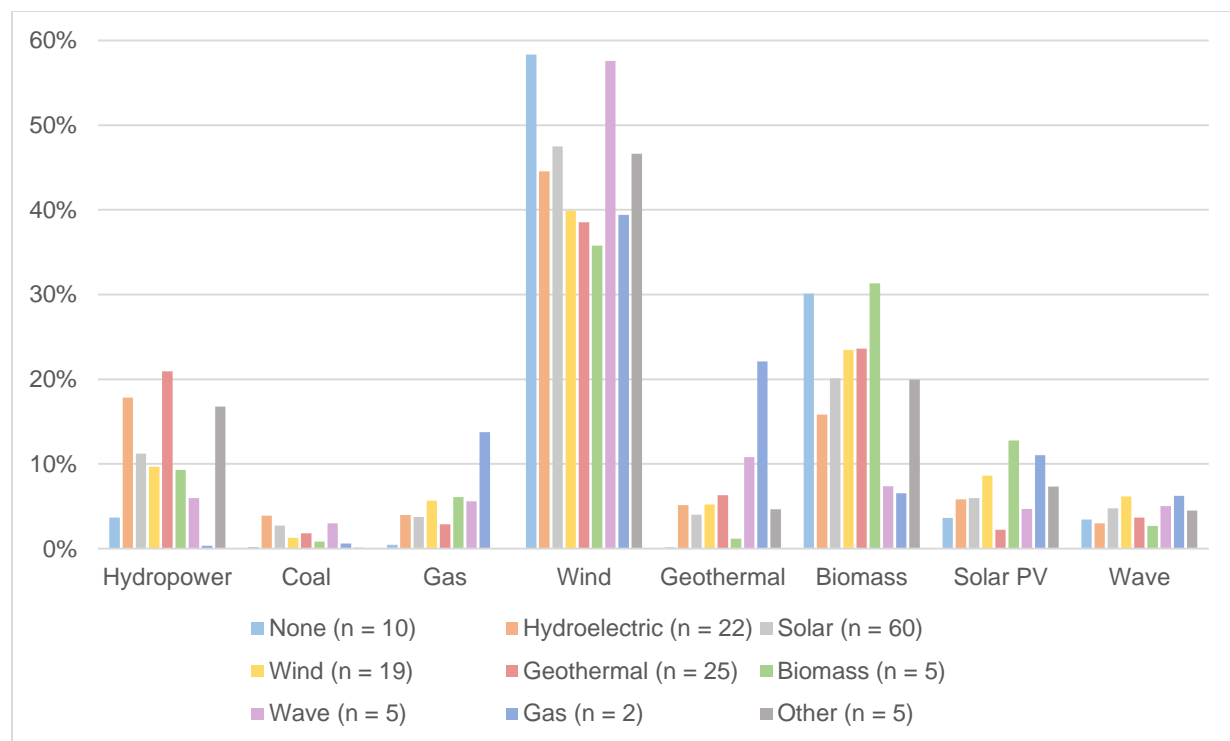


Figure 36 Energy source selection in market simulator by theoretically preferred source

Source: developed by author.

4.4.4. SOCIAL IMPACT CONVERTED TO MARGINAL WILLINGNESS TO PAY (MWTP)

In this section social impacts are converted into MWTP to, in monetary terms, evaluate the publics' preference of an energy system based on their acceptance or aversion to a systems attributes. To determine the MWTP the model described by (Takahashi & Sato, 2015) was followed.

Figure 39 summarizes the influence of public preference on the price of one kW for each energy source. As is observable, cost and low coverage are the main causes of a reduced price for wave and solar energy. However, in the case of solar PV, a small increase would still be attainable due to its performance in environmental aspects.

Geothermal is mainly affected by its hydrological footprint. While gas and coal would be significantly punished because of their carbon emissions.

On the other hand, wind, biomass, and hydropower would observe important net increases based on preference of the respondents towards the values presented by these energy sources in the survey.

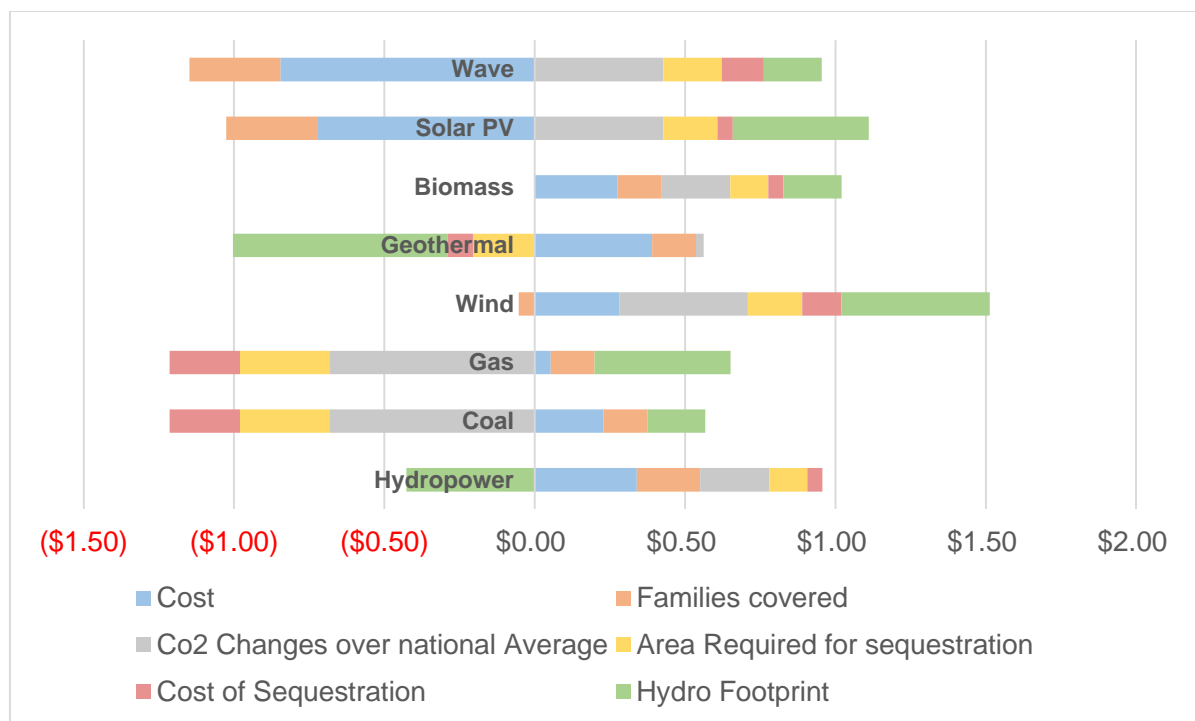


Figure 37 Composition of social impact effects on MWTP for energy sources

Source: developed by author.

Taking into consideration all effects of social preference on the price of a kW, we can determine the net price of each energy source as presented in Table 22. Noticeably, wind energy would have a significant increase in price over any other energy source, while coal would have the most important reduction.

Table 22 MWTP (\$/kWh) considering social impact

Energy Source	\$ / kWh
Hydropower	\$ 0.205
Coal	\$ 0.061
Gas	\$ 0.071
Wind	\$ 0.319
Geothermal	\$ 0.086
Biomass	\$ 0.265
Solar PV	\$ 0.151
Wave	\$ 0.116

Source: developed by author.

Finally, net social impact expressed in monetary terms can be observed in the following Figure. Geothermal energy would be the most affected energy system, primarily because of its hydrological footprint, while biomass would be the leading benefactor.

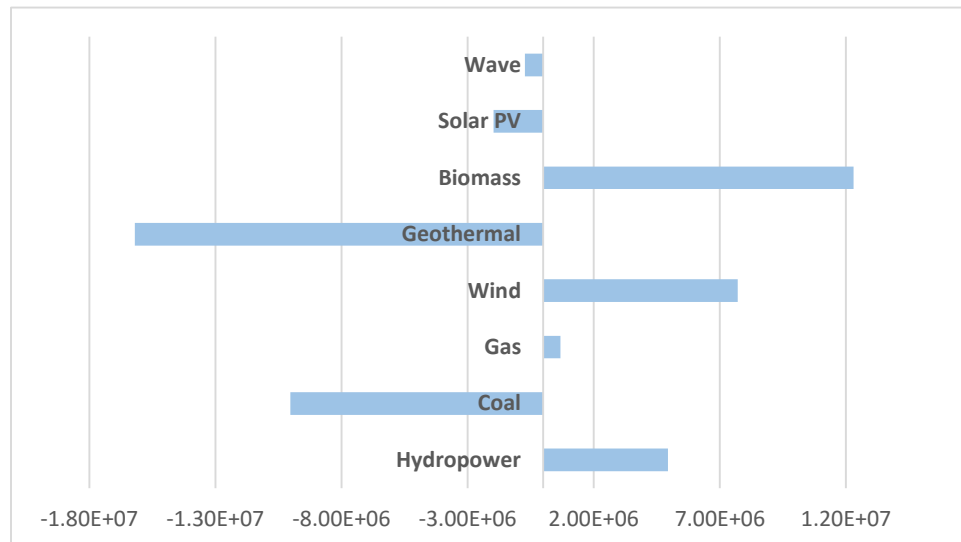


Figure 38 Net Social Impact in (USD)

Source: developed by author.

4.5. TRIPLE I INDEX

Triple I Index (III) allows for the results of Ecological Footprint, Cost Benefit analysis, and the Social Impact study to come together in a simple manner that is easily understandable. Furthermore, the particular version of III index utilized was converted to Triple I Social, to include the weight of public acceptance in the measurement because, as stated by (Takahashi & Sato, 2015) “Public acceptance is one of the most important issues when considering the sustainability of anthropogenic systems. The development of energy systems in the future will depend on the balance of environmental impact, economic feasibility, and public acceptance.” In addition, due to the novel nature of wave energy and the lack of data for an adequate calculation of Human or Environmental Risks of this source in Costa Rica, beyond theoretical predictions, the selected version of III would be the most adequate.

Moreover, this study has slightly adapted III_{social} index developed by Takahashi and Sato, so that Social Impact could be calculated in monetary terms instead of in global hectares with the goal of simplifying survey for respondents. Subsequently results can be presented in monetary terms, considered to be simpler to understand for lay people than global hectares.

The Equation for the adapted III_{Social} is expressed as follows:

Equation 7 Adapted III_{Social} Index

$$III = \gamma EF + (C - B + S_{\text{impact}})$$

Where:

γ : EF – Currency coefficient (1.19)

EF: Ecological footprint

C: Cost

B: Benefit

S_{impact} : Social impact

Source: adapted by author from (Takahashi & Sato, 2015).

Final calculations utilizing III, are done for both scenarios developed in the Cost Benefit analysis section of this chapter, comparing the effects of S_{Impact} and EF on these cases. Adapted wave energy scenario is not developed, because it is considered to be highly unlikely.

The initial results presented are for the systems financed through a loan. This scenario is considered to be the most realistic and that with lowest risk for investors. The systems resulting

with a net benefit are hydropower, biomass and wind energy. While geothermal and coal, which originally were considered a viable option, are no longer in the positive. Wave energy and solar PV, are the energy sources with the most negative impact.

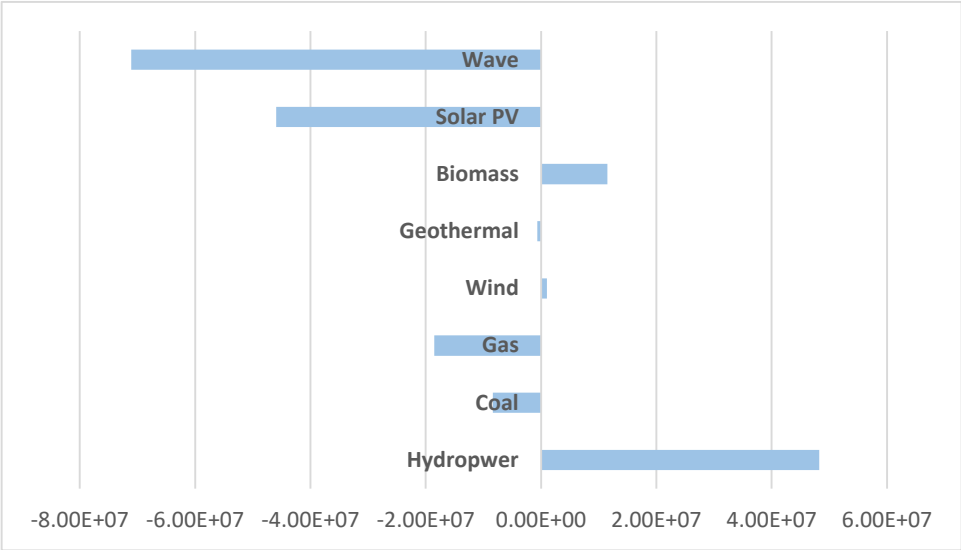


Figure 39 III of financed energy systems measured in USD

Source: developed by author.

A closer look at the composition of III for finances systems, allows to visualize how social impact of biomass system for example, was sufficient to shift it from a net loss to a net gain position.

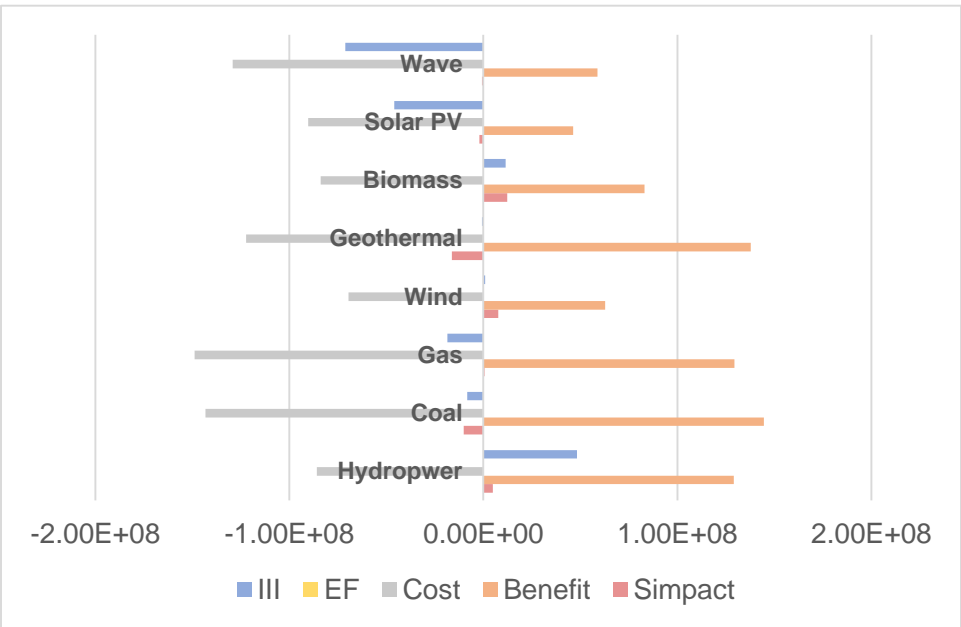


Figure 40 Composition of III of financed energy systems measured in USD

Source: developed by author.

In the scenario for systems that did not count with a loan and were self-financed, biomass is still on the positive end, yet significantly closer to break-even. However, in difference to traditional CB, wind energy becomes a viable option.

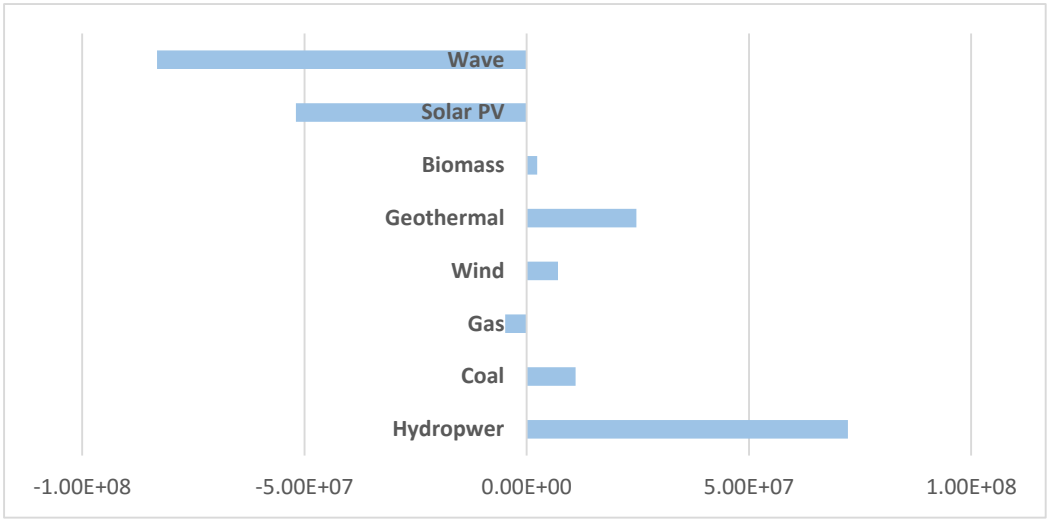


Figure 41 III of self-financed energy systems measured in USD

Source: developed by author.

For the case of self-financed systems, social impact and ecological footprint would consider hydropower and geothermal energies the most worthwhile systems.

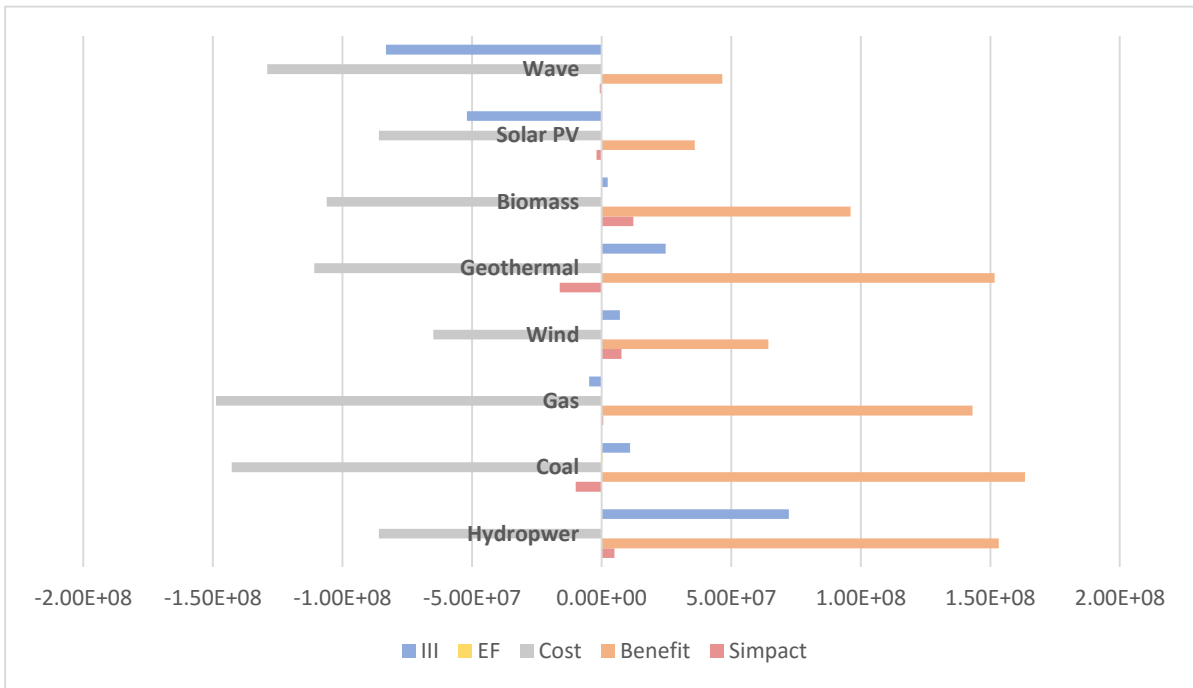


Figure 42 Composition of III of self-financed energy systems measured in USD

Source: developed by author.

4.6. WAVE ENERGY EVALUATION SUMMARY

In terms of ecological footprint, wave energy is the source that generates the least carbon emissions of all systems. Furthermore, if we evaluate a scenario where the totality of families without access to electricity service were covered by wave energy, a little over 32 MW would have to be installed. The EF of wave energy in this scenario, would still be lower than that of all other sources (measured at 10 MW) except for hydropower with a difference of only 72 tons and wind.

When evaluating the Social Impact of wave energy, besides cost, the only area in which the source is punished is that of coverage caused by a low capacity factor (efficiency). Nevertheless, we can assume that with technological development this could be significantly improved and thus enhance the acceptance of wave energy. Furthermore, when evaluating the composition of S_{Impact} for wave energy, the largest negative effect was that of generation cost; if we excluded this section from the evaluation, wave energy would have had a net benefit increasing its MWTP and acceptance. In environmental terms it was very positively evaluated.

Finally, the Cost Benefit analysis which resulted the most significant weight in the evaluation for the sheer magnitude of costs has an important limitation caused by the lack of local data. Costs are defined based on international averages and reported projects in the past, while they are expected to have important variations in the future due to technological development. Furthermore, the experimental sites for ocean energies are located in countries with conditions knowingly different than those of Costa Rica, such as Scotland. Therefore, capital costs, maintenance and operation could prove to be different in the tropical nation.

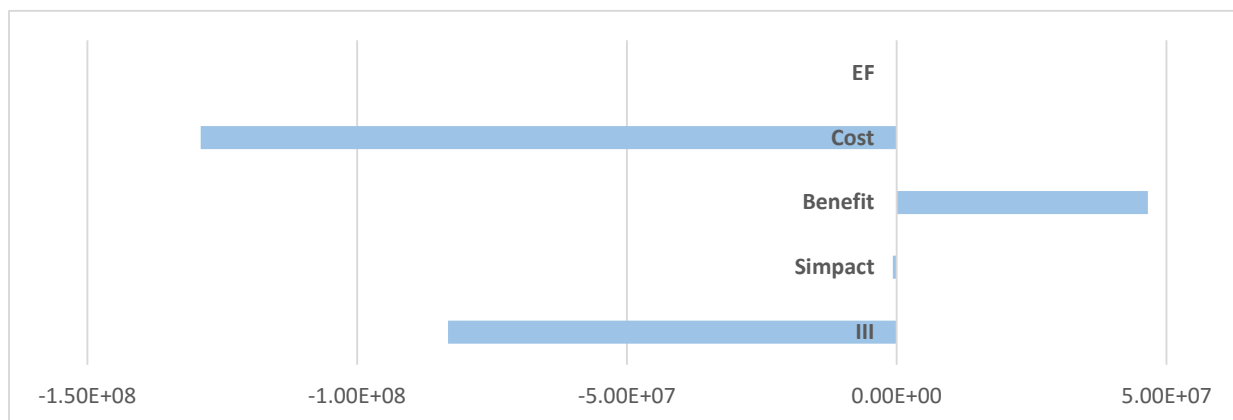


Figure 43 Wave energy summary

Source: developed by author.

5. CONCLUSION

Current chapter concludes this research by presenting mayor discussion points and identifying potentials for future research. It presents reflections of environmental, economic and social aspects which are presented for the consideration in next stages of project and policy development.

5.1. SIGNIFICANCE OF THE STUDY

This study evaluated the possibilities of diversifying the energy mix with carbon neutral energy systems to attain Sustainable Energy for All. Additionally, it assessed the possibility of introducing ocean energy produced by waves, as a means to achieve the established goals. It identified economic barriers in the pricing of electricity that limit diversification of the energy mix. Lack of market flexibility reduces viability of energy systems, especially those desired for attainment of a more diversified and decentralized national energy system that could provide higher stability to the grid, while reducing costs and emissions.

Ocean energy was analyzed in terms of environmental, socio-political and economic variables. Considering current costs for electricity generation and initial investment prohibitively high. The scenarios for ocean energy to be economically viable were determined. Gaps in policy for implementation and potential social conflicts are determined, yet need to be further analyzed.

The study analyzed the differences between financed and self-financed systems, to better determine which possibilities can be considered by private investors with access to finance or private funds and which would most efficiently be developed by government. Additionally, the possibility to increase renewable energy production from sources like wind energy and biomass is deemed viable, and could be considered desirable in specific scenarios. Contrary to the institutional preferences within ICE, geothermal is less desirable for the general public than expected.

Potential market niches are identified for specific sources. As well as a gap between energy source claimed to be preferred and that actually selected when focusing on the attributes of each energy system. Public preference of energy sources is evaluated and MWTP of individual systems considering social impacts was determined. The impacts on project viability of

incorporating Ecological Footprint and Social Impact as well as traditional Cost Benefit studies is determined.

5.2. LIMITATIONS

Main limitations in this study are identified in the lack of available information on wave energy systems; especially those with installed capacities above 10 MW and those with benefits associated with larger scale of projects. Furthermore, cost of energy generation are based on international standards which would require conversion to local terms, when data is accessible.

By analyzing a completely inelastic supply model, under valuations could have occurred where energy systems in reality could increase production and potentially become viable.

Development of social impact survey via web although reduces costs significantly, may produce bias of populations that have most access to internet services, like the urban areas of Costa Rica. Access to communities without electric service may also be relevant yet are excluded in this study.

5.3. FUTURE RECOMMENDATIONS

Supplementary studies are required to better represent national population and reduce any potential bias amongst survey respondents. Evaluating mechanisms to simplify social impact assessment to reduce incomplete participations by respondents could provide results with higher confidence levels, and more respondents concluding the questionnaire.

Furthermore, considering that amongst NTRE wind and biomass energy systems are those with the highest potentials of viability and present relatively low environmental impacts, additional studies to more adequately define the potentials these systems present for the diversification of energy mix are considered relevant. An additionally study to further elucidate on the reasons for the gap between the preferred energy sources and those originally claimed as preferred is suggested.

A comparative study between wind energy and off-shore wind is recommended to analyze the possibilities of reduced social rejection caused by NIMBY effect of traditional wind energy systems, and the viability of this energy source in the Costa Rican market.

If wave energy is still to be considered by government, for its social or potentially low environmental implications, especially if costs continue decreasing as expected, further studies to advance in the determination of impact on marine biology and marine climatological conditions are required.

Finally, further studies to adequately price electricity without significantly affecting the industrial sector are recommended.

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7. APPENDIXES

APPENDIX 1 CONJOINT ANALYSIS MODEL QUESTIONS


First stage (attribute weight definition) sample question:

Evaluación de preferencias - Fuentes energéticas

Cada planta energética produce cantidades de electricidad diferentes según sus condiciones específicas (fuente, tecnología, etc). Si usted fuera a producir energía para brindarla al sector residencial, como evaluaría la cobertura en cuanto a cantidad de familias* que recibirían el servicio?

*Se asume que cada familia cuenta en promedio con cuatro (4) personas. Calculo para una planta de 10 MW para distintas tecnologías.

	Inaceptable	Aceptable	Preferible	Sin opinion
Más de 30,000	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Entre 20,000 y 29,999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Entre 10,000 y 19,999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Menos de 9,999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>



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La información recolectada será utilizada únicamente por el encuestador con fines académicos, no será utilizada de ninguna forma con fines comerciales, ni transferida a terceros. No se publicará ninguna información que permita identificarle como encuestado.

Esto es un ejercicio académico para optar por el grado de master en ciencias sostenibles de la Universidad de Tokyo en Japón. Si tuviera alguna consulta, favor contactar al encuestador al correo: roastro@sustainability.k.u-tokyo.ac.jp

Evaluating amount of families covered by production in terms of: unacceptable, acceptable, preferable, or no opinion. Each level of the attribute must contain a response.

Translation:

Every power plant produces different amounts of energy depending on its specific characteristics (source, technology, etc). If you were to produce energy for the residential sector, how would you evaluate coverage based on amount of families* that would receive the service.

*Assume every family consists of four (4) people in average. Calculation for a power plant of 10 MW installed capacity of different technologies.

	Unacceptable	Acceptable	Preferable	No opinion
More than 30 000	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Between 20 000 and 29 999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Between 10 000 and 19 999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Less than 9 999	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Second stage (CBC analysis) sample question:

Evaluación de preferencias - Fuentes energéticas

Construiremos una nueva planta energética de 10 MW y hemos solicitado su asistencia para seleccionar la tecnología a utilizar. ¿Si las siguientes opciones fueran las únicas posibilidades, cual elegiría?

– *Seleccione aquella opción (columna) que contenga la variable o mezcla de variables de su preferencia, o bien NINGUNA si no hay opción de su agrado.*

Los rangos de las variables pueden ser encontrados en el siguiente enlace: [Matriz de evaluación](#)

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Costo por kilowatt	\$0.100	\$0.120	\$0.060	\$0.050	\$0.098	NINGUNA: No elegiría ninguna de las opciones.
Familias Cubiertas por producción	Más de 30,000	Entre 10,000 y 19,999	Entre 10,000 y 19,999	Menos de 9,999	Menos de 9,999	
Cambio en emisiones anuales	Reducción alta	Reducción baja	Reducción media	Incremento	Reducción alta	
Hectáreas de bosque requeridas	Alto	Medio	Bajo	Muy alto	Cero	
Gasto en certificados de emisiones	Alto	Medio	Cero	Muy alto	Bajo	
Consumo anual de agua	Bajo	Muy alto	Cero	Alto	Medio	
	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>



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La información recolectada será utilizada únicamente por el encuestador con fines académicos, no será utilizada de ninguna forma con fines comerciales, ni transferida a terceros. No se publicará ninguna información que permita identificarle como encuestado.

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Respondent must select one option containing an energy scenario composed of attributes from different sources. The respondent may also select none, when no scenario is of his liking.

Translation:

A new 10 MW power plant will be constructed and we require your assistance to determine which technology to utilize. If the following options were the only available in the market, which would you select?

-Select the option (column) that has the attribute or attributes of your preference, or NONE if no option pleases you.

The ranges for the attributes can be found in the following link: [Evaluation Matrix](#)

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Cost per kilowatt	\$0.100	\$0.120	\$0.060	\$0.050	0.098	NONE: I would not select any of the options.
Families covered by production	More than 30 000	Between 10 000 and 19 999	Between 10 000 and 19 999	Less than 9 999	Less than 9 999	
Changes in annual emissions	High reduction	Low reduction	Medium reduction	Increase	High reduction	
Hectares of forest required	High	Medium	Low	Very high	Zero	
Cost of sequestration	High	Medium	Zero	Very high	Low	
Water consumption	Low	Medium	Zero	High	Medium	
	O	O	O	O	O	O

APPENDIX 2 CONJOINT ANALYSIS MATRIX

	Area (ha)	Annual Cost of Sequestration	Hydrological Footprint (l)
Very High	More than 4 000	More than \$100,000	More than 1 000 000
High	Between 1 000 and 3 999	Between \$35 000 and \$99 999	Between 500 000 and 999 999
Medium	Between 100 and 999	Between \$5 000 and \$34 999	Between 100 000 and 499 999
Low	Less than 100	Less than \$4 999	Less than 100 000
None	Does not require because no emissions are produced	Does not require carbon bonds because no emissions are produced	Does not consume water during energy generation

	Changes in CO ₂ emissions
Increased	More than 9 000 t of CO _{2eq} over national average are emitted
Small reduction	Up to 4 499 t of CO _{2eq} less than average emissions are produced
Medium reduction	Emissions are reduced in the magnitude of 4 500 to 8 999 t of CO _{2eq} less than average emissions are produced
High reduction	Less than 9 000 t of CO _{2eq} below national average are produced

APPENDIX 3 CONJOINT ANALYSIS COMPLETE DEMOGRAPHICS

Respondents by sex

Sex	Total
Male	95
Female	58

Respondents by age ranges

Age ranges	Total
< 18	0
18 - 24	8
25 - 34	60
35 - 44	25
45 - 54	27
55 - 64	30
65 - 74	3
> 75	0

Respondents by province in which they live

Province	Total
San José	94
Heredia	28
Alajuela	11
Cartago	12
Guanacaste	1
Puntarenas	4
Limón	3

Respondents by status and sector of employment

Occupation	Total
Unemployed	8
Student	16
Employed (Academia)	14
Employed (Public sector)	33
Employed (Private sector)	71
Employed (NGOs)	11

Respondents by highest level of education achieved

Level of Education	Total
None	0
Elementary School (incomplete)	0
Elementary School (complete)	0
High School (incomplete)	1
High School (complete)	0
Technical / Vocational	4
College (incomplete)	12
College Bachelor	21
Specialized Bachelor	47
Masters	54
Doctorate	14
Other	0

Respondents by age and sex

	Male	Female
< 18	0	0
18 - 24	6	2
25 - 34	31	29
35 - 44	14	11
45 - 54	17	10
55 - 64	25	5
65 - 74	2	1
> 75	0	0
Subtotal	95	58

Respondents by age and level of education

	None	Elementary School (incomplete)	Elementary School (complete)	High School (incomplete)	High School (complete)	Technical / Vocational	College (incomplete)	College Bachelor	Specialized Bachelor	Masters	Doctorate	Other
< 18	0	0	0	0	0	0	0	0	0	0	0	0
18 - 24	0	0	0	0	0	2	2	3	1	0	0	0
25 - 34	0	0	0	0	0	1	3	11	27	17	1	0
35 - 44	0	0	0	1	0	1	1	4	6	10	2	0
45 - 54	0	0	0	0	0	0	2	3	6	13	3	0
55 - 64	0	0	0	0	0	0	3	0	6	13	8	0
65 - 74	0	0	0	0	0	0	1	0	1	1	0	0
> 75	0	0	0	0	0	0	0	0	0	0	0	0
Subtotal	0	0	0	1	0	4	12	21	47	54	14	0

Respondents by age and province

	San José	Heredia	Alajuela	Cartago	Guanacaste	Puntarenas	Limón
< 18	0	0	0	0	0	0	0
18 - 24	3	0	0	1	1	2	1
25 - 34	41	8	6	4	0	1	0
35 - 44	14	5	3	3	0	0	0
45 - 54	15	7	1	4	0	0	0
55 - 64	19	7	1	0	0	1	2
65 - 74	2	1	0	0	0	0	0
> 75	0	0	0	0	0	0	0
Subtotal	94	28	11	12	1	4	3

Respondents by age and occupation

	Unemployed	Student	Employed (Academia)	Employed (Public sector)	Employed (Private sector)	Employed (NGOs)
< 18	0	0	0	0	0	0
18 - 24	1	5	0	1	1	0
25 - 34	3	10	3	11	28	5
35 - 44	1	0	4	6	11	3
45 - 54	1	0	3	9	11	3
55 - 64	0	1	4	6	19	0
65 - 74	2	0	0	0	1	0
> 75	0	0	0	0	0	0
Subtotal	8	16	14	33	71	11

Respondents by age and theoretically preferred energy source

	None	Hydroelectric	Solar	Wind	Geothermal	Biomass	Wave	Coal	Gas	Other
< 18	0	0	0	0	0	0	0	0	0	0
18 - 24	0	1	2	2	1	1	1	0	0	0
25 - 34	6	6	28	9	7	0	4	0	0	0
35 - 44	1	5	4	2	7	4	0	0	1	1
45 - 54	1	6	13	1	3	0	0	0	0	3
55 - 64	2	4	12	4	7	0	0	0	0	1
65 - 74	0	0	1	1	0	0	0	0	1	0
> 75	0	0	0	0	0	0	0	0	0	0
Subtotal	10	22	60	19	25	5	5	0	2	5

Respondents by sex and level of education

	None	Elementary School (incomplete)	Elementary School (complete)	High School (incomplete)	High School (complete)	Technical / Vocational	College (incomplete)	College Bachelor	Specialized Bachelor	Masters	Doctorate	Other
Male	0	0	0	0	0	2	7	15	24	34	13	0
Female	0	0	0	1	0	2	5	6	23	20	1	0
Subtotal	0	0	0	1	0	4	12	21	47	54	14	0

Respondents by sex and province

	San José	Heredia	Alajuela	Cartago	Guanacaste	Puntarenas	Limón
Male	55	19	7	8	1	2	3
Female	39	9	4	4	0	2	0
Subtotal	94	28	11	12	1	4	3

Respondents by sex and occupation

	Unemployed	Student	Employed (Academia)	Employed (Public sector)	Employed (Private sector)	Employed (NGOs)
Male	4	8	10	19	47	7
Female	4	8	4	14	24	4
Subtotal	8	16	14	33	71	11

Respondents by sex and theoretically preferred energy source

	None	Hydroelectric	Solar	Wind	Geothermal	Biomass	Wave	Coal	Gas	Other
Male	4	14	39	9	18	4	4	0	0	3
Female	6	8	21	10	7	1	1	0	2	2
Subtotal	10	22	60	19	25	5	5	0	2	5

Respondents by level of education and province

	San José	Heredia	Alajuela	Cartago	Guanacaste	Puntarenas	Limón
None	0	0	0	0	0	0	0
Elementary School (incomplete)	0	0	0	0	0	0	0
Elementary School (complete)	0	0	0	0	0	0	0
High School (incomplete)	0	1	0	0	0	0	0
High School (complete)	0	0	0	0	0	0	0
Technical / Vocational	4	0	0	0	0	0	0
College (incomplete)	8	0	1	0	0	2	1
College Bachelor	11	3	0	4	0	2	1
Specialized Bachelor	30	9	3	4	1	0	0
Masters	34	10	7	2	0	0	1
Doctorate	7	5	0	2	0	0	0
Other	0	0	0	0	0	0	0
Subtotal	94	28	11	12	1	4	3

Respondents by level of education and occupation

	Unemployed	Student	Employed (Academia)	Employed (Public sector)	Employed (Private sector)	Employed (NGOs)
None	0	0	0	0	0	0
Elementary School (incomplete)	0	0	0	0	0	0
Elementary School (complete)	0	0	0	0	0	0
High School (incomplete)	1	0	0	0	0	0
High School (complete)	0	0	0	0	0	0
Technical / Vocational	0	1	0	0	3	0
College (incomplete)	2	3	0	0	7	0
College Bachelor	0	3	0	6	10	2
Specialized Bachelor	3	4	1	12	23	4
Masters	2	5	5	13	24	5
Doctorate	0	0	8	2	4	0
Other	0	0	0	0	0	0
Subtotal	8	16	14	33	71	11

Respondents by level of education and theoretically preferred energy source

	None	Hydroelectric	Solar	Wind	Geothermal	Biomass	Wave	Coal	Gas	Other
None	0	0	0	0	0	0	0	0	0	0
Elementary School (incomplete)	0	0	0	0	0	0	0	0	0	0
Elementary School (complete)	0	0	0	0	0	0	0	0	0	0
High School (incomplete)	0	0	0	0	0	0	0	0	1	0
High School (complete)	0	0	0	0	0	0	0	0	0	0
Technical / Vocational	0	0	3	0	1	0	0	0	0	0
College (incomplete)	1	0	4	4	1	1	0	0	1	0
College Bachelor	0	4	10	4	1	0	2	0	0	0
Specialized Bachelor	6	7	18	6	6	1	2	0	0	1
Masters	1	8	22	4	13	2	1	0	0	3
Doctorate	2	3	3	1	3	1	0	0	0	1
Other	0	0	0	0	0	0	0	0	0	0
Subtotal	10	22	60	19	25	5	5	0	2	5

Respondents by province and occupation

	Unemployed	Student	Employed (Academia)	Employed (Public sector)	Employed (Private sector)	Employed (NGOs)
San José	5	9	6	21	46	7
Heredia	2	3	4	3	14	2
Alajuela	0	1	2	0	7	1
Cartago	0	1	2	7	2	0
Guanacaste	1	0	0	0	0	0
Puntarenas	0	2	0	0	1	1
Limón	0	0	0	2	1	0
Subtotal	8	16	14	33	71	11

Respondents by province and theoretically preferred energy source

	None	Hydroelectric	Solar	Wind	Geothermal	Biomass	Wave	Coal	Gas	Other
San José	9	15	33	17	13	0	4	0	1	2
Heredia	0	3	12	0	9	1	0	0	1	2
Alajuela	1	0	6	0	2	1	0	0	0	1
Cartago	0	3	5	1	1	2	0	0	0	0
Guanacaste	0	0	0	1	0	0	0	0	0	0
Puntarenas	0	1	1	0	0	1	1	0	0	0
Limón	0	0	3	0	0	0	0	0	0	0
Subtotal	10	22	60	19	25	5	5	0	2	5

Respondents by occupation and theoretically preferred energy source

	None	Hydroelectric	Solar	Wind	Geothermal	Biomass	Wave	Coal	Gas	Other
Unemployed	1	0	1	3	0	0	1	0	2	0
Student	2	3	5	1	3	1	1	0	0	0
Employed (Academia)	1	2	4	2	1	2	0	0	0	2
Employed (Public sector)	1	8	15	4	3	1	1	0	0	0
Employed (Private sector)	5	7	33	7	14	1	2	0	0	2
Employed (NGOs)	0	2	2	2	4	0	0	0	0	1
Subtotal	10	22	60	19	25	5	5	0	2	5