100% RENEWABLE ENERGY FOR COSTA RICA

A decarbonization roadmap.

2020

About the Authors

The Institute for Sustainable Futures (ISF) was established by the University of Technology Sydney in 1996 to work with industry, government, and the community to develop sustainable futures through research and consultancy. Our mission is to create change towards establishing sustainable futures that protect and enhance the environment, human well-being, and social equity. We use an inter-disciplinary approach to our work and engage our partner organisations in a collaborative process that emphasises strategic decision-making.

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Energy Models

Utility-scale solar photovoltaic and wind power potential were mapped with [R]E-SPACE, a mapping tool developed by the Institute for Sustainable Futures of the University of Technology Sydney (ISF-UTS) based on QGIS (open source).
The long-term energy scenario software for the long-term projections and economic parameters is based on the development of the German Aerospace Centre (DLR), Institute for Technical Thermodynamics, (Pfaffenwaldring 38-40, 70569 Stuttgart, Germany) and was applied to over 100 energy scenario simulations for global, regional, and national energy analyses.
Regional *Power Analysis* calculated with [R]E 24/7 was developed by Dr. Sven Teske (PhD), with further developments by ISF-UTS.

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EXECUTIVE SUMMARY

The World Future Council and La Ruta del Clima/Costa Rica commissioned this report, financed by the One Earth Foundation USA to provide input into Costa Rica's plan to achieve 100% renewable energy. Costa Rica is a global leader when it comes to ensuring energy production comes from renewable energy sources. With a 98% share of renewables in its electricity matrix and solid achievements to prevent deforestation—around 25% of the country's land area is in protected National Parks and other protected areas—Costa Rica is at the forefront environmental sustainability, climate action and driving the renewable energy transition.

Wanting to go even further, Costa Rica has adopted the *National Decarbonization Plan* in February 2019 to achieve a net-zero emissions economy by 2050, in line with the objectives of the Paris Climate Change Agreement. The planned measures, activities and improvements also form part of the country's extended Nationally Determined Contributions (NDCs) that Costa Rica will present in 2020 to the UNFCCC to demonstrate and strengthen its commitment to reduce greenhouse gas emissions and participate in the global effort to avoid a temperature rise above 1.5 degrees Celsius with respect to the pre-industrial era.

As the Costa Rican President, Carlos Alvarado Quesada, noted during the launch of the Plan, "Decarbonization is the great challenge of our generation and Costa Rica must be among the first countries to achieve it, if not the first."

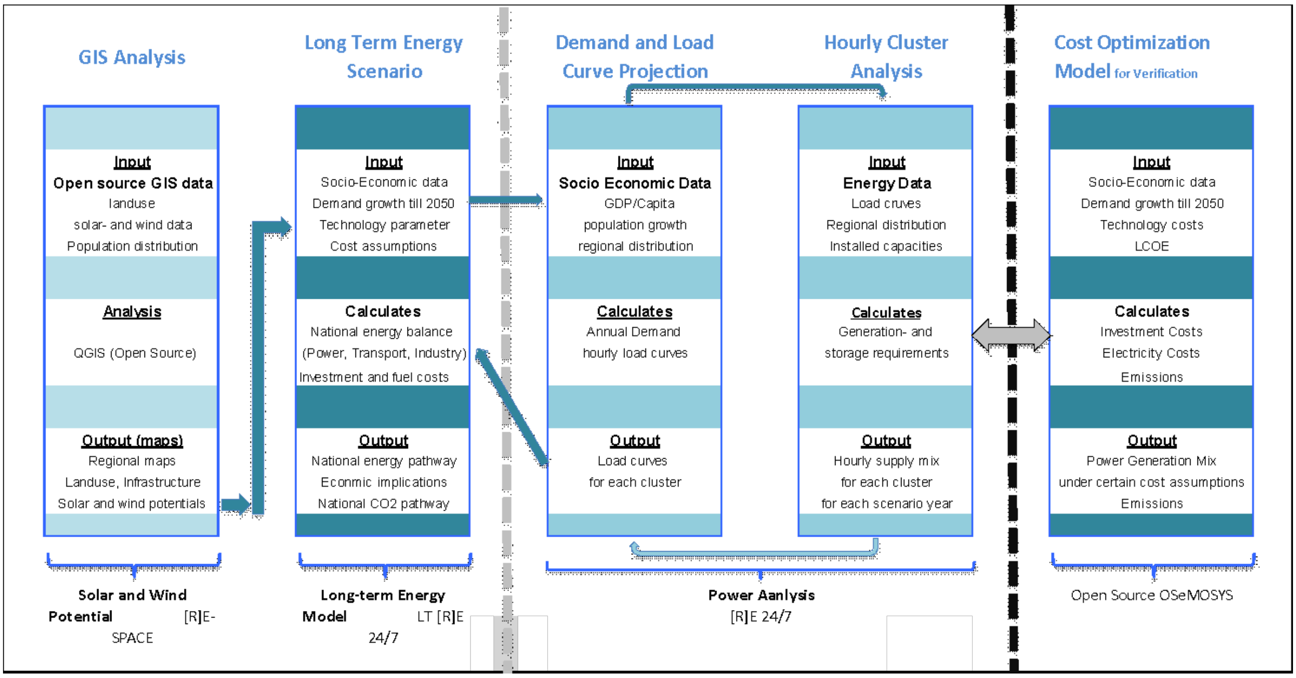
The biggest challenge will be to increase the share of renewables in energy consumption. More than 60% of energy consumption in the country is from petroleum derivatives. 64% of Costa Rica's emissions come from energy use, and more than two thirds of that is from transport. A critical part will thus be to decarbonize the transport sector. The growing demand for personal vehicles, the majority of which run on petrol, is keeping a high share of fossil fuels in the country's energy consumption. The Decarbonization Plan aims to have 70 percent of public transport powered by electricity in 2035—and the whole fleet by 2050.
This study aims to complement these efforts and show pathways to 100%RE in order to meet the decarbonisation challenge.

- **Solar PV:** Costa Rica has 203,000 MW of utility-scale solar PV potential. Even the most ambitious 100%RE scenario can be implemented with the utilisation of only 6% of the utility-scale solar power plant potential (196 GW). In addition, San José has significant potential for rooftop solar photovoltaic.
- **Wind:** Costa Rica has around15 GW worth of on-shore wind potential and an additional 21 GW offshore wind potential. However, due to off-shore wind resources being located in marine protected areas, they are not utilised in the study. However, the wind resource is concentrated in only one region—Guanacaste—therefore transmission capacity needs to be increased to distribute the electricity across the country.
- **Generation costs:** implementing 100%RE will save almost US$1cent per kWh power generation.
- **Investments and savings:** For the whole modelling period until 2050, the Reference and the RE1 scenarios have similar investment needs of US$ 30 billion over 30 years. The RE2 scenario requires higher investments – a total of US$ 40 billion over the same period of time, due to higher electricity needs as a result of the electrification of the transport sector. The fuel cost savings will reach up to US$ 5.3 billion up to 2050 (US$180 million per year), which will cover 84% of the total additional investments compared with the Reference scenario.
- **Transport:** The transport sector can be electrified up to 78% with increased share of renewables. Hydrogen and other synthetic fuels generated with renewable electricity may be complementary for the transport sector, but have not been considered in all scenarios.
- **Heating:** The heating sector can be completely decarbonised by 2040. Biomass will remain the main contributor, with increasing investment in highly efficient modern biomass technologies. After 2025, a massive growth in solar collectors and increasing proportions of geothermal and environmental heat will further reduce the dependence on fossil fuels.
- **Infrastructure:** To harvest Costa Rica's onshore wind and solar resources, as well as geothermal and bio energy potential, the power grid must be able to transport large loads from the west coast further inland, whereas decentralized power will shoulder a significant part of the residential sector demand. Onshore wind requires transmission lines to the load centres of Costa Rica.

Storage: The majority of storage facilities will be required in Guanacaste because this region has Costa Rica's largest wind resources and a significant proportion of the wind generation is concentrated here. For the whole of Costa Rica, the required estimated storage capacity will be between 1.0% and 3.5% in 2050.

This research was led by the University of Technology Sydney–Institute for Sustainable Futures (UTS-ISF). This report provides a technical and economic analysis of long-term energy and power development plans for Costa Rica. The analysis is based on the [R]E24/7 energy access pathway methodology developed by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS) and is based on the long-term energy scenario model of the Institute for Thermodynamics of German Aero Space Centre (DLR), energy models developed for various UTS-ISF surveys, and the [R]E 24/7 model. Figure 1 provides an overview of the models used and their interactions.

Figure 1: Overview—Modelling concept



In the mapping analysis, a global information system (GIS) was used for the regional analysis of Costa Rica's population density and distribution, its solar and wind resources, and the currently existing energy infrastructure (transmission power lines and power plants with over 100 MW installed capacity). This information has been used to define the cluster breakdown.

The long-term scenario—LT [R]E 24/7—has been used to re-model the *Plan de Expansion de La Generation Electrica* (GEP 2019)[6] which was published in May 2019 (see section 1) and to develop alternative national energy pathways for Costa Rica. This model considers all sectors (power, heat, and transport) and includes cost and energy-related CO_2 calculations.

The [R]E 24/7 power sector analysis tool computes the annual demand for up to five different years (here 2020, 2030, 2040, and 2050) and the load curves for a full year (8760 h). The hourly load curves are required for the simulation of the demand and supply for each of the seven regions of Costa Rica. The results are the development of loads, generation mix, and storage demand.

Socio-economic data

Projections of population and economic growth are important factors in building energy scenarios because they affect the size and composition of the energy demand, both directly and through their impact on economic growth and development.

The current population of Costa Rica is 5 million, an increase from the 4.58 million at the 2011 census. This makes Costa Rica the 120th most populous country in the world. Population growth has remained steady at around 1% per year. 80% of the country's population live in a city or a surrounding urban area. The capital and largest city is San José, with a population of about 335,000 and a high population density of 6,455 people per square kilometre. The greater metropolitan area has 2.15 million residents or a third of the country's entire population. In 2018, the life expectancy at birth for Costa Ricans was 79.8 years, ranking the country 29th in the world in terms of longevity.

According to projections[1], the population of Costa Rica will grow by 4% per year until 2025 to 5.25 million people. The population growth is estimated to slow down to around 3% by 2030 and to 1.5% by 2040. Based on these estimates, the population will increase to 5.76 million by 2050 (see Table 1).
For the development of the energy scenario, it is assumed that Costa Rica's economic development will grow by 2.75% per year until 2035 and by 2% until 2050.

Table 1: Costa Rica—Population and GDP projections

	t	2017	2020	2025	2030	2035	2040	2045	2050
GDP	[billion US$$_{2010}$/a]	58.2	63	72	82	94	104	115	127
GDP/Person	[US$/capita]	11,867	12,438	13,696	15,200	16,987	18,416	20,081	22,022
Population	[million]	4.902	5.044	5.246	5.413	5.548	5.650	5.721	5.759
			2017–2020	**2020–2025**	**2025–2030**	**2030–2035**	**2035–2040**	**2040–2045**	**2045–2050**
Economic growth	[%/a]		2.75%	2.75%	2.75%	2.75%	2.00%	2.00%	2.00%
Population growth	[%/a]		4.7%	4.0%	3.4%	2.7%	2.0%	1.4%	0.8%

The electricity demand projections documented in this section were calculated for the residential and business sectors with the [R]E 24/7 model in a bottom-up process. The further electricity demand entailed by transport (especially under the two alternative scenarios, with increased electric mobility) and by the internal electricity demand of power plants ("own consumption"), and the distribution losses are calculated with the long-term model (see sections 2.2 and 4.2) and added to the calculated demand projections. However, the [R]E 24/7 power analysis only considers the additional electricity demand for distribution losses, because the power plant consumption does not influence storage or grid requirements.

[1] The Population Pyramid, Online database, viewed September 2019, https://www.populationpyramid.net/costa-rica/2050/

Projected development of electricity demand

The development of industry and business demand is based on the GDP breakdown (Table 2). It assumes that the overall structure of the economy does not change and that all sectors grow at rates equal to that of GDP over the entire modelling period. Table 3 shows the assumed breakdown of GDP by sub-category. The shares are based on CIA (2019)[2].

Table 2: Development of GDP shares by industry sector across all regions of Costa Rica (2017)

Industry	20.5%
Manufacturing	10.0%
Mining	2.0%
Iron + Steel	1.0%
Cement	1.0%
Construction	5.5%
Energy intensive industry	1.0%
Services	73.5%
Offices & Services	65.5%
Tourism	8.0%
Agriculture	6%
Agriculture	6%

The GDP distribution by region is based on 2017 data and is assumed to remain the same for the entire modelling period, until 2050. In the industry sector, an efficiency gain of 0.5% per year has been calculated between 2020 and 2030 and of 0.75% per year between 2031 and 2050. In the service and agricultural sectors, an efficiency development of 0.5% per year until 2030 has been calculated, with 0.25% for the rest of the modelling period.

Table 3: Development of Costa Rica's shares of GDP by region

Region	[%]
Alajuela	20%
Cartago	11%
Guanacaste	8%
Heredia	10%
Limon	9%
Puntarenas	10%
San Jose	33%

Cost projections

The speed of an energy system transition depends, to some extent, on overcoming the economic barriers. These largely relate to the relationships between the costs of renewable technologies and those of their fossil and nuclear counterparts. The projection of these costs for the various scenarios is vital to ensure that valid comparisons of energy systems are made. However, there have been significant limitations to these projections, in the past in terms of investment and fuel costs. Moreover, efficiency measures also generate costs, which are usually difficult to determine, depending on the technical, structural, and economic boundary conditions. During the last decade, fossil fuel prices have seen huge fluctuations. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar fluctuations. Therefore, fossil fuel price projections have also varied considerably and have had a considerable influence on the scenario outcomes ever since, especially those scenarios that are based on cost optimization algorithms.

Most renewable energy technologies provide energy with no fuel costs, so the projections of investment costs become more important than the fuel cost projections, and this limits the impact of errors in the fuel price projections. Fuel costs are only important for biomass-based energy generation because the cost of feedstock remains a crucial economic factor. Today, these costs range from negative costs for waste wood (based on credits when waste disposal costs are avoided), through inexpensive residual materials, to comparatively expensive energy crops.

[2] CIA 2019, Central Intelligence Agency, The World Factbook, Central America / Costa Rica, Page last updated October 24, 2019, https://www.cia.gov/library/publications/the-world-factbook/geos/cs.html

Table 4: Investment cost assumptions for power generation plants (in US$/kW) until 2050

Assumed Investment Costs for Power Generation Plants						
		2017	**2020**	**2030**	**2040**	**2050**
Coal power plant	$/kW	1,816	1,816	1,816	1,816	1,816
Lignite power plant	$/kW	1,998	1,998	1,998	1,998	1,998
Gas power plant	$/kW	608	454	454	454	608
Oil power plant	$/kW	863	845	808	781	745
Diesel generator	$/kW	817	817	817	817	817
Nuclear power plant	$/kW	5,993	5,449	4,631	4,086	4,086
Co-Generation– fossil						
CHP coal	$/kW	1,456	1,456	1,456	1,456	1,456
CHP gas	$/kW	510	510	510	510	510
CHP lignite	$/kW	1,456	1,456	1,456	1,456	1,456
CHP oil	$/kW	957	937	899	861	823
Renewables						
Biomass power plant	$/kW	2,179	2,134	2,089	1,998	1,916
Hydro power plant	$/kW	4,200	4,200	4,100	4,100	4,100
Wind turbine offshore	$/kW	2,200	2,100	1,371	1,317	1,271
Wind turbine onshore	$/kW	3,632	3,351	2,897	2,570	2,370
Photovoltaic, rooftop	$/kW	1,418	1,181	663	509	427
Photovoltaic—utility scale	$/kW	1181	890	663	509	427
Geothermal power plant	$/kW	7,700	7,700	7,500	6,600	6,500
CSP power plant (incl. storage)	$/kW	5,176	4,540	3,360	2,770	2,488
Ocean energy power plant	$/kW	6,311	6,039	3,996	2,815	1,916
Hydrogen production	$/kW	1253	1108	835	636	518
Co-Generation–renewable						
CHP biomass	$/kW	1,820	1,784	1,747	1,675	2,460
CHP fuel cell	$/kW	4540	4540	2270	2270	1017
CHP geothermal	$/kW	9,610	8,147	6,476	5,432	4,700

*Costs for a system with a solar multiple of two and thermal storage for 8 h of turbine operation
**Values apply to both run-of-the-river and reservoir hydro power

Table 5: Development projections for fossil fuel prices

Development projections for fossil fuel prices						
All Scenarios		2017	2020	2030	2040	2050
Biomass	$/GJ	7.80	13.80	20.10	26.20	30.60
Oil	$/GJ	6.58	8.80	11.80	13.40	14.50
Gas	$/GJ	12.58	13.60	14.00	14.40	14.80
Coal	$/GJ	1.95	2.21	3.18	3.50	3.80
Nuclear	$/GJ	0.9	0.9	1.1	1.3	1.5

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions on INEC (2018)[6] and LAZARDS (2018)[3]. Although these price projections are highly speculative, they provide a set of prices consistent with our investment assumptions. For bioenergy,

[3] LAZARDS (2018); Lazard's Levelized Cost of Energy Analysis—Version 12.0, November 2018

we assumed that fuels will be supplied from harvesting and process residuals in a price range of $3/GJ to $5/GJ (IRENA 2014)[4]

Assessment of solar and wind potential

Costa Rica has a largely untapped potential for renewable energy, and the only resource used significantly is biomass as well as hydro power. Biomass and geothermal resources are utilized in both the heating and power sectors. Hydro power has only minor potential for further increase because Costa Rica's utilization rate for hydro power plants is already close to the maximum level in terms of sustainability.

Solar energy is abundant, with excellent potential for utility-scale photovoltaic power stations. The three regions with the highest potential for utility scale solar photovoltaics are Guanacaste, Alajuela and Puntarenas. However, solar photovoltaic is surprisingly underutilized compared with the available solar resource and the low generation costs. This is due to unfavourable policy regarding grid connections, feed-in rates, and construction permits.

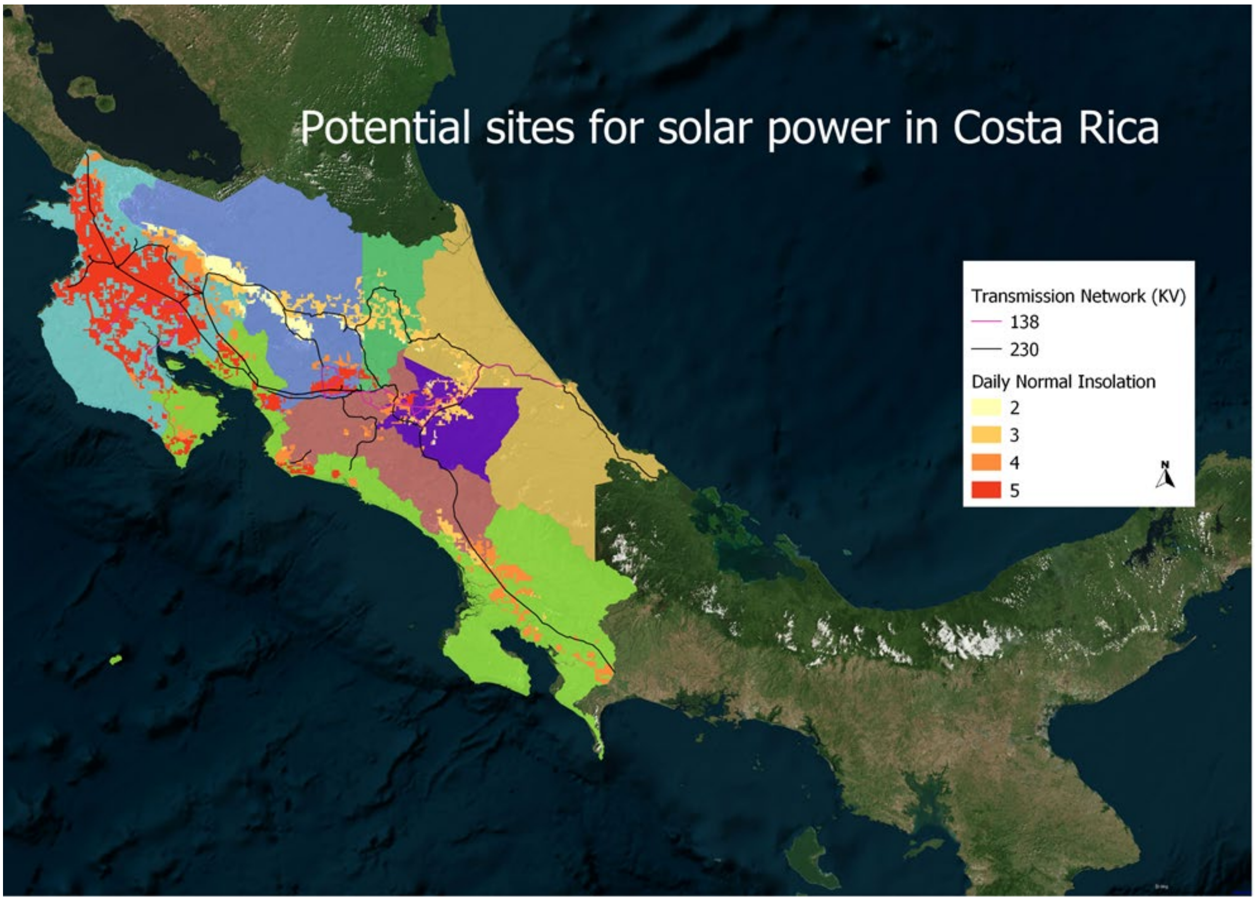
Costa Rica's wind resources are concentrated in the north-western region of Guanacaste, which extends between Lake Managua and the Pacific Coast. Off-shore wind has not been considered in this study, due to its close proximity to protected areas. Table 6 shows Costa Rica's potential for utility-scale solar and wind power generation under the most restricted scenarios described in section 3.5.

Table 6: Overview—Costa Rica's utility-scale solar photovoltaic, onshore wind, and offshore wind potential within 10 km of existing power lines

Cluster	Solar Area in km^2	Solar Potential in GW	Onshore Wind Area in km^2	Onshore Wind Potential in GW
Alajuela	1,584.01	39.60	472.81	1.89
Cartago	483.89	12.10	89.62	0.36
Guanacaste	3,734.38	93.36	3,101.44	12.41
Heredia	381.13	9.53	29.81	0.12
Limon	271.59	6.79	-	-
Puntarenas	1,112.53	27.81	80.92	0.32
San Jose	283.15	7.08	19.42	0.08
Total	7,850.68	196.27	3,794.03	15.18

[4] IRENA (2014), Global Bioenergy Supply and Demand Projections: A working paper for Remap 2030, International Renewable Energy Energy Agency, Abu Dhabi, United Arab Emirates

Figure 2: Potential for utility-scale solar energy generation in Costa Rica



Source: ISF mapping, July 2019

Assumptions for the scenarios

In February 2019, the government launched its *Decarbonization Plan*, which defines activities in key sectors to be implemented in three steps until 2050 in order to achieve a modern, emission-free, resilient and inclusive economy.[5] The Plan underpins the National Plan for Development and Public Investments and the long-term Plan Estratégico Costa Rica 2050. To reach this goal, Costa Rica will make changes and modifications to mobility and transport (both public and private), optimize energy management, promote sustainable construction and industry, and improve recycling and waste disposal. The Plan offers a roadmap to promote the modernization of Costa Rica's economy, generate jobs, and boost its growth, based on the generation of "3D" services and goods: Decarbonized, Digitized and Decentralized. The planned measures, activities, and improvements also form part of the country's extended Nationally Determined Contributions (NDCs), which Costa Rica will present in 2020 to the UNFCCC. It will thus demonstrate and strengthen its commitment to reducing greenhouse gas emissions and to its participation in the global effort to avoid a temperature rise above 2 °C with respect to the pre-industrial era.

The REFERENCE scenario in this analysis is consistent with the *Plan de Expansión de La Generación Eléctrica* of May 2019 and suggests two additional scenarios, which go further in the deployment of renewable energy and energy efficiency across all sectors. The scenario-building process for all scenarios includes assumptions about policy stability, the role of future energy utilities, centralized fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Costa Rica will establish a secure and stable framework for the deployment of renewable power generation. In essence, financing a gas power plant or a wind farm is quite similar. In both scenarios, a power purchase agreement, which ensures a relatively stable price for a specific quantity of electricity, is required to finance the project. Daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any kind of power plant with a technical lifetime of 20 years or longer. In short, the better the investment certainty, the lower the cost of capital.
- **Strengthened energy efficiency policies:** Existing policy settings (i.e., the energy efficiency standards for electrical applications, buildings, and vehicles) must be strengthened to maximize the cost-efficient use of renewable energy and achieve high energy productivity by 2030.
- **Role of future energy utilities:** With the 'grid parity' of rooftop solar photovoltaics below most current retail tariffs, this modelling assumes that energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** All three scenarios are based on the same population and GDP assumptions. The projections of population growth are documented in Table 11 in section 2.4.
- **Cost assumptions:** The same cost assumptions are used across all three scenarios. Because technology costs decline as the scale of deployment increases rather than with time, the renewable energy cost reduction potential in both RENEWABLES scenarios may be even larger than in the REFERENCE scenario because of the larger market sizes. The reverse is true for the fuel cost assumptions because all the scenarios are based on the same fossil fuel price projections, but whereas both RENEWABLES scenarios have a significant drop in demand, the REFERENCE scenario assumes an increased demand, which may lead to higher fuel costs. Therefore, these costs should be considered conservative. The cost assumptions are documented in section 5.3.

[5] https://presidencia.go.cr/wp-content/uploads/2019/05/National-Decarbonization-Plan-Costa-Rica.pdf

Key results—long-term scenario

In the executive summary, we focus on the key results for the power sector and the primary energy demand. The results for the transport and heating sectors are documented in section 3.

Electricity generation

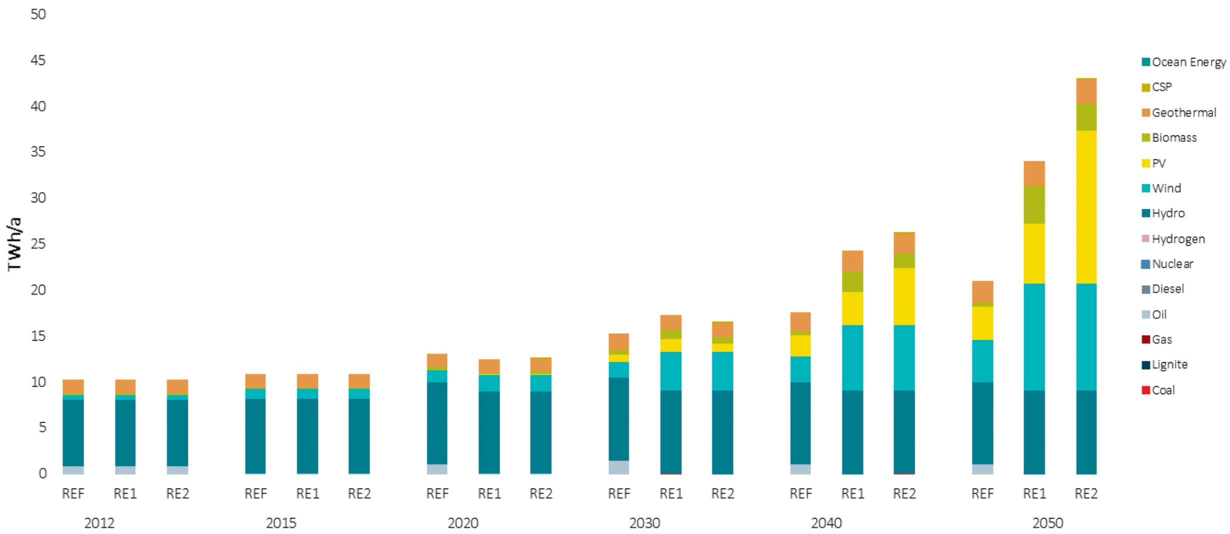
The development of the electricity supply sector will be characterized by a dynamically growing renewable energy market and an increasing share of renewable electricity. This trend will more than compensate the phase-out of oil power plants by 2025 and the increased electricity demand due to electric mobility under both alternative scenarios. By 2030, 100% of the electricity produced in Costa Rica will come from renewable energy sources in all scenarios. In the RE1 scenario, 'new' renewables—mainly solar photovoltaic and onshore wind—will contribute 33% to the total electricity generated in 2030 and 54% by 2050. The installed capacity of renewables will reach close to 5,500 MW in 2030 and 12,800 MW by 2050.

Table 7: Costa Rica—Projections of renewable electricity generation capacity

In MW		2015	2020	2030	2040	2050
Hydro	REF	1,935	2,356	2,375	2,375	2,375
	RE1	1,935	2,342	2,401	2,401	2,401
	RE2	1,935	2,342	2,401	2,401	2,401
Biomass	REF	40	82	85	86	104
	RE1	40	43	167	403	793
	RE2	40	48	120	285	555
Wind	REF	396	408	490	810	1,318
	RE1	396	737	1,552	2,527	4,115
	RE2	396	737	1,552	2,527	4,116
Geothermal	REF	208	262	322	375	415
	RE1	208	262	322	336	385
	RE2	208	262	322	336	385
Photovoltaic (PV)	REF	3	28	585	1,517	2,472
	RE1	3	35	1,093	2,770	5,080
	RE2	3	56	741	4,762	12,857
Total	REF	2,682	3,123	3,858	5,165	6,684
	RE1	2,681	3,347	5,437	8,417	12,774
	RE2	2,681	3,384	5,038	10,290	20,313

The RE2 scenario will also achieve 100% renewable electricity generation in 2030. However, the renewable capacity will increase after 2030 beyond the RE1 values due to more-ambitious electric mobility. By 2040, the capacity will reach 10,300 MW and 20,300 MW in 2050, around 8,000 MW higher than under the RE1 scenario. Table 7 shows the comparative evolution of the different renewable technologies in Costa Rica over time. The installed capacity of hydro power will dominate as the major renewable power capacity over decades, but will be taken over by solar photovoltaics in 2040 and will remain the largest renewable power capacity through-out the remaining scenario period. Wind power will increase in both RENEWABLES scenarios to just over 4,000 MW, whereas hydro power will remain on around 2,400 MW. Both renewable scenarios will result in a high proportion of variable power generation (photovoltaics and wind): 33%–31% by 2030 and 54%–66% by 2050. Therefore, smart grids, demand-side management, energy storage capacities, and other options must be expanded to increase the flexibility of the power system to ensure grid integration, load balancing, and a secure supply of electricity.

Figure 3: Costa Rica—Breakdown of electricity generation by technology



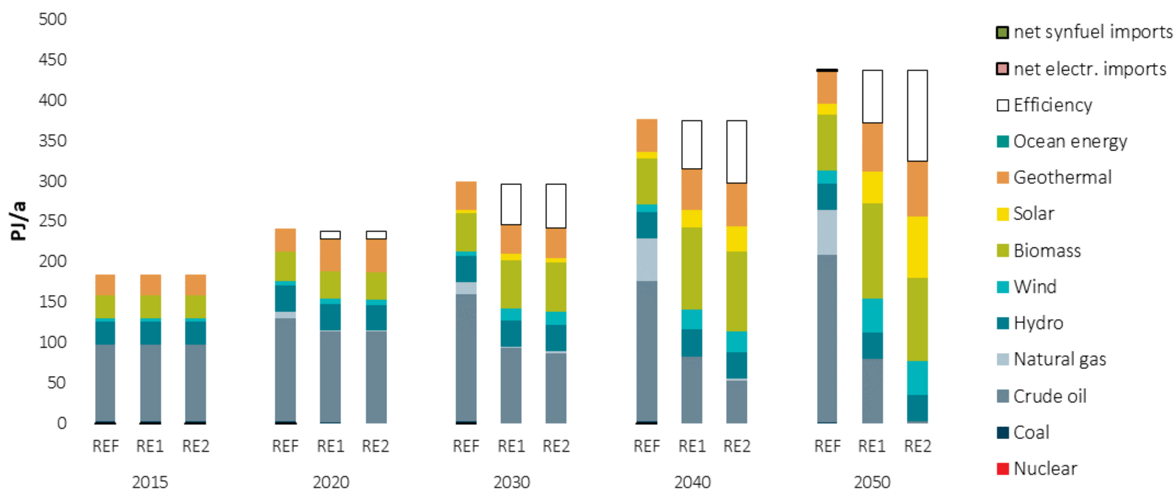
The calculated potential for utility-scale solar power plants (photovoltaic, PV) under all restrictions and excluding areas further than 10 km from transmission lines is 203,000 MW. Even the most ambitious RE2 scenario can be implemented with the utilisation of only 6% of the utility-scale solar power plant potential. Additional to this potential, Costa Rica has significant rooftop solar PV potential. The RE1 scenario has less solar photovoltaic power generation and wind power generation because of the lower electrification rates in the industry and transport sectors.

In terms of onshore wind, both alternative scenarios use around 25% of the onshore wind potential, with the highest restriction identified in section 3.5.1 until 2050. However, the wind resource is concentrated in only one region, Guanacaste, so the transmission capacity must be increased to distribute the electricity across the country (see section 5).

Primary energy

Based on the assumptions discussed above, the primary energy consumptions under both RENEWABLES scenarios and the REFERENCE scenario are shown in Figure 4. Under the RE1 scenario, the primary energy demand will increase from the present level of around 185 PJ/a to around 250 PJ/a in 2030, a reduction of 34%. Compared with the REF scenario, the overall primary energy demand will be reduced by 52 PJ by 2030 under the RE1 scenario (REF: 298 PJ in 2030). The RE2 scenario will result in primary energy consumption of around 242 PJ in 2030. In comparison, the REF scenario leads to 437 PJ/a by 2050, whereas the RENEWABLES scenarios will; result in 372 PJ/a (RE1) and 325 PJ/a (RE2).

Figure 4: Costa Rica—Projection of total primary energy demand by energy carrier (incl. electricity import balance)



The RENEWABLES scenarios aim to reduce the fossil fuel consumption as fast as is technically and economically possible by the expansion of renewable energy generation and the rapid introduction of very

efficient vehicles into the transport sector to replace oil-based combustion engines. This will lead to an overall renewable primary energy share of 61% in 2030 and 78% in 2050 in the RE1 scenario and 100% in 2050 in the RE2 scenario (excluding non-energy consumption).

Power sector analysis

Costa Rica's current plans for the future development of the power capacities (GEP)[6] will maintain a share of over 90% renewable electricity, but will not be sufficient to supply the transport sector to satisfy the additional power demand in the face of a shift of electric mobility. Therefore, the transport sector will be increasingly dependent on imported oil, and carbon emissions would continue to rise, even with a decarbonized power sector. The current installed power plant capacity will reach 3.5 GW, with a majority of hydro power (2.4 GW). The capacity of solar photovoltaics and onshore wind will increase under all three scenarios. However, the solar photovoltaic market varies significantly. Whereas the annual average market until 2025 will range around only 3 MW per year under the REFERENCE scenario, RE1 requires an annual installation of 15 MW and the RE2 scenario 85 MW. However, after 2025, the solar photovoltaic market will grow substantially in all scenarios reflecting the cost advantages for solar systems. The wind market will significantly increase and will reach around 175 MW per year at the end of the modelling period – between 2040 and 2050. Almost all wind farms will be located in Guanacaste, the province with the most favourable wind resource. Furthermore, Costa Rica will increase its geothermal capacities as projected under the *Generation Expansion Plan* (GEP)[6]. Additional bio-energy capacity will add to the diverse renewable power generation mix after 2025.

Development of load, generation and residual load

Table 8: Costa Rica—Projection of load, generation, and residual load until 2050

Costa Rica Development of load and generation		REF				RE1				RE2			
		Max. Demand	Max. Generation	Max. Residual Load	Peak load increase	Max Demand	Max Generation	Max Residual Load	Peak load increase	Max Demand	Max Generation	Max Residual Load	Peak load increase
Costa Rica		[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]
Alajuela	2020	0.4	0.3	0.2	100%	0.4	0.4	0.2	100%	0.5	0.5	0.1	100%
	2030	0.5	0.5	0.1	113%	0.6	0.5	0.2	128%	0.6	0.6	0.1	118%
	2050	0.7	0.7	0.3	165%	1.0	1.0	0.5	228%	1.2	2.4	0.8	231%
Cartago	2020	0.2	0.4	0.0	100%	0.2	0.4	0.0	100%	0.3	0.6	0.1	100%
	2030	0.2	0.5	0.0	113%	0.3	0.5	0.0	128%	0.3	0.6	0.0	118%
	2050	0.4	0.7	0.1	165%	0.5	0.8	0.0	228%	0.6	1.1	0.1	231%
Guanacaste	2020	0.2	0.3	0.0	100%	0.2	0.3	0.0	100%	0.2	0.3	0.1	100%
	2030	0.2	0.7	0.0	111%	0.2	1.5	0.1	126%	0.2	1.5	0.0	116%
	2050	0.2	1.8	0.1	151%	0.4	4.1	0.1	215%	0.4	4.6	0.2	220%
Heredia	2020	0.2	0.2	0.0	100%	0.2	0.2	0.1	100%	0.3	0.3	0.1	100%
	2030	0.2	0.2	0.1	111%	0.3	0.3	0.1	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.2	151%	0.5	0.5	0.2	215%	0.6	1.2	0.4	220%
Limon	2020	0.2	0.2	0.0	100%	0.2	0.3	0.0	100%	0.2	0.4	0.1	100%
	2030	0.2	0.2	0.0	111%	0.2	0.2	0.0	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.1	152%	0.4	0.5	0.2	216%	0.5	1.0	0.3	221%
Puntarenas	2020	0.2	0.2	0.0	100%	0.2	0.2	0.1	100%	0.3	0.3	0.1	100%
	2030	0.2	0.2	0.1	111%	0.3	0.2	0.1	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.2	152%	0.5	0.5	0.2	216%	0.6	1.2	0.4	221%
San Jose	2020	0.6	0.5	0.2	100%	0.6	0.6	0.2	100%	0.7	0.9	0.2	100%
	2030	0.7	0.7	0.2	130%	0.9	0.8	0.3	144%	1.0	1.0	0.1	131%
	2050	1.1	1.2	0.6	195%	1.6	1.6	0.8	259%	1.9	3.8	1.1	261%
Costa Rica	2020	2.0	2.2	0.6	100%	2.1	2.4	0.6	100%	2.5	3.3	0.7	100%
	2030	2.3	3.1	1.0	112%	2.7	4.1	1.0	127%	3.0	4.7	0.3	117%
	2050	3.3	5.4	2.0	156%	4.8	8.9	2.0	220%	5.9	15.3	3.1	224%

Figure 8 shows that Costa Rica's average load is predicted to increase over the next decade by approximately 15% under the REFERENCE and RENEWABLES 1 scenarios, and by 27% under the

RENEWABLES 2 scenario. The RE2 scenario will have the highest peak load by 2050, as a result of increased electrification of the heating and transport sectors, and the energy efficiency targets are more ambitious than under the RE1 scenario. The RE2 scenario has a stringent electrification strategy, especially in the transport sector, with an earlier phase-out target for fossil fuels for the transport sector, but a more ambitious energy efficiency strategy. In comparison, the load under RE1 in 2050 will be 1.5 GW higher than in the REF scenario, but 1.1 GW lower than under the RE2 scenario.

Although there are regional differences, load will increase in percentage across all regions quite similarly. However, the actual loads will be significantly different between the regions. The lowest peak load will be in Guanacaste in 2050, of only 400 MW, whereas the maximum calculated generation capacity will reach 4,600 MW. However, the San José region will continue to have the highest peak load at around 1,900 MW (RE2), with maximum generation of 3,800 MW, which is twice the maximum demand. This is an indication of the need to introduce energy efficiency parallel to the implementation of electric mobility to limit the required investment in the upgrade of Costa Rica's power grid infrastructure. However, in any case and independent of the type of power generation, the power grid must by expanded over the next two decades, because increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. However, the locations of transmission grids will be dependent on the form of generation because the locations of generation and the demand centres may differ for decentralized and centralized power generation.

Storage requirements

The quantity of storage required is largely dependent on the storage costs, grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than storage costs. In general terms, PV-dominated grids correlate directly with high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap.

In all scenarios, the share of variable generation will not exceed 30% by 2030 in any region, except in one, Guanacaste, where the share will already be around 80%.

The REFERENCE scenario requires the lowest storage capacity for Costa Rica, with the majority concentrated in the wind-dominated region. The oversupply in the North West region will result from the high installed capacity (relative to the local load) of onshore wind. The RE1 scenario will lead to around 2.5 times higher storage capacity than the REFERENCE scenario, all of which will be located in Guanacaste. By 2030, only one region will require storage in all scenarios, whereas by 2040, storage will be required in all seven regions. The storage requirements have been assessed based on the assumptions that all the regions will have established interconnection capacities, as indicated in section 4.3, and that the economic curtailment rates will be fully exhausted.

Table 9 gives an overview of the estimated storage capacity requirements for both RENEWABLES scenarios. The majority of storage facilities will be required in Guanacaste because this regions has Costa Rica's largest wind resources and a significant proportion of wind generation will be concentrated here. For the whole of Costa Rica, the required estimated storage capacity will be 1.0% of the total variable generation in 2050 under the RE1 scenario, and 3.5% under the RE2 scenario. However, there will be significant regional differences. To remain within the economic curtailment range, storage will be required in all regions under both scenarios. For the whole of Costa Rica, the simulation of renewable power generation in scenarios RE 1 and RE2 will lead to storage requirements of 76 GWh/a and 719 GWh/a, respectively, with installed input/output capacities of 60–100 MW and around 600 MW, respectively. The requirement for utility-scale storage will occur by 2030. The storage demand will vary significantly and will be a function of the regional distribution of variable power generation and the extent to which the regions can exchange load via interconnections.

The storage capacity in electric vehicles is not included in this calculation and is assumed to be used for load management via charging strategies, but not as storage capacities for stationary power system requirements.

Table 9: Costa Rica—Estimated electricity storage requirements for both RENEWABLES scenarios

Storage requirement to avoid curtailment		REF		RE1		RE2	
		Total storage throughput	Storage capacity (1)	Total storage throughput	Storage capacity (1)	Total storage throughput	Storage capacity (1)
Costa Rica		[GWh/a]	[GW/a]	[GWh/a]	[GW/a]	[GWh/a]	[GW/a]
Alajuela	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	8.657	0.007	7.261	0.006	140.446	0.117
Cartago	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	3.826	0.003	0.000	0.000	80.407	0.067
Guanacaste	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	13.906	0.012	10.666	0.009	11.088	0.009
	2050	50.143	0.042	43.639	0.036	51.491	0.043
Heredia	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	23.028	0.019	9.997	0.008	78.406	0.065
Limon	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	12.000	0.010	1.384	0.001	71.035	0.059
Puntarenas	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	9.051	0.008	12.572	0.010	81.067	0.068
San Jose	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	15.176	0.013	1.025	0.001	215.837	0.180
Total	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	13.906	0.012	10.666	0.009	11.088	0.009
	2050	121.881	0.102	75.878	0.063	718.690	0.599

(1 (1) Calculated with an average capacity factor of 1,200 hours per year

Summary power sector analysis for Costa Rica

Both RENEWABLES scenarios prioritize the use of Costa Rica's renewable energy resources to reduce its dependence on oil imports for the growing transport demand, by electrification. Costa Rica will significantly increase its power demand under each power generation scenario. Therefore, power grids must expand, and power generation must increase as the load increases, under all scenarios. However, the electrification of the transport sector in combination with renewable-energy-dominated power generation requires a different infrastructural design than an oil-dominated transport sector. To harvest Costa Rica's onshore wind and solar resources, as well as its geothermal and bio energy potential, the power grid must be able to transport large loads from the west coast further inland, whereas decentralized power will shoulder a significant part of the residential sector demand. Onshore wind requires transmission lines to the load centres of Costa Rica.

In 2050, the majority of system services (ancillary and dispatch) power will come from bio energy, geothermal power, and hydro power, which may be operated with onside storage technologies after 2030. Costa Rica has abundant renewable energy resources, which could supply, with the currently available technologies, all the renewable electricity required to power the traditional power sector and shoulder the increased electricity demand for electric vehicles. However, more research is required to assess how electric mobility can be integrated into the power sector to provide load and demand management and to use storage capacities as efficiently as possible.

1 METHODOLOGY AND ASSUMPTIONS

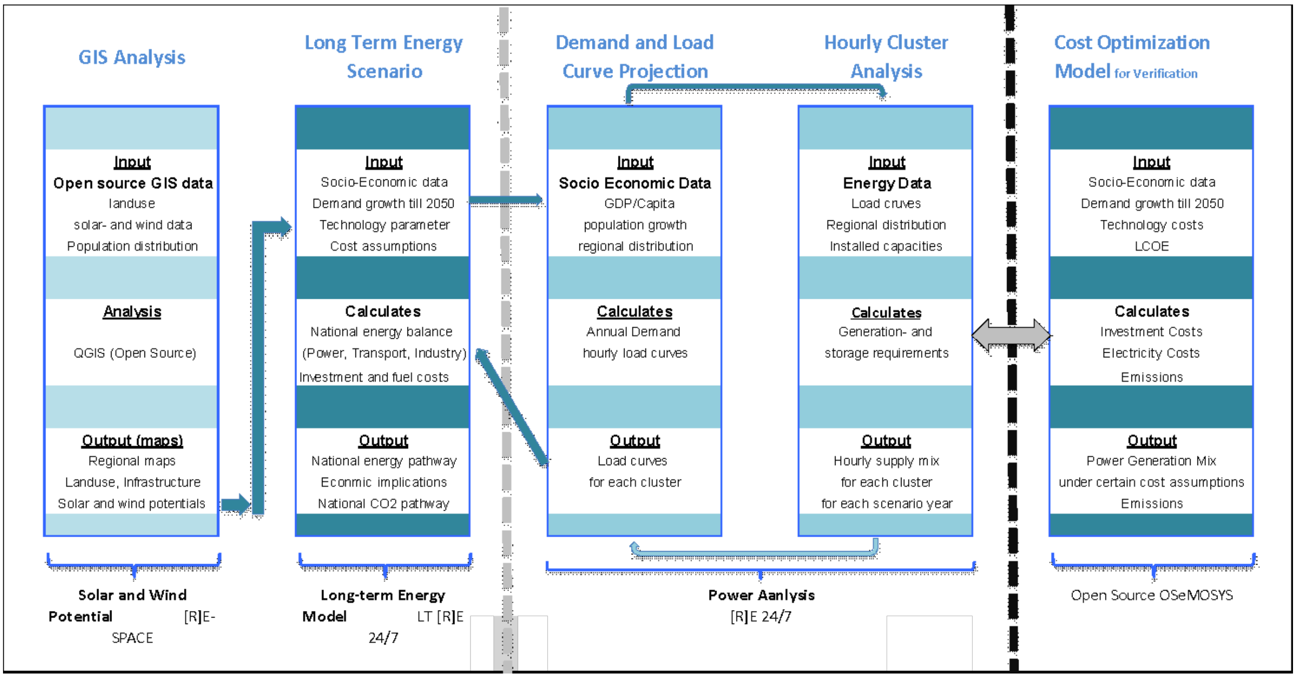
This report provides a technical and economic analysis of the long-term energy and power development plans for Costa Rica. The analysis is based on the [R]E 24/7 energy access pathway methodology developed by the Institute for Sustainable Futures (ISF) at the University of Technology Sydney (UTS) and on the long-term energy scenario model of the Institute for Thermodynamics of German Aero Space Centre (DLR), energy models developed for various UTS-ISF surveys, and the [R]E 24/7 model. The following section explains the methodology and provides an overview of the required input parameters, basic functions, and calculated outputs. The entire modelling process is based on four modules developed by UTS-ISF. The models are described below in their order of use.

In the mapping analysis, a global information system (GIS) was used for a regional analysis of Costa Rica's population density and distribution, its solar and wind resources, and the currently existing energy infrastructure (transmission power lines and power plants with over 100 MW of installed capacity). This information has been used to define the cluster breakdown.

The long-term scenario LT [R]E 24/7 has been used to re-model the existing power development plan and to develop alternative national energy pathways for Costa Rica. This model takes all sectors into account (power, heat, and transport) and includes cost and energy-related CO_2 calculations.

The [R]E 24/7 power sector analysis tool computes the annual demand for up to five different years (here: 2020, 2030, 2040, and 2050) and the load curves for a full year (8760 h). The hourly load curves are required to simulate the demand and supply for each of the seven regions of Costa Rica. The results are the development of loads, the generation mix, and the storage demand.

Figure 5: Overview—Modelling concept



1.1 [R]E 24/7—GIS MAPPING TOOL

The primary purpose of GIS mapping is to ascertain the renewable energy resources (primarily solar and wind) available in Costa Rica. It also contributes to the regional analysis of geographic and demographic parameters and the available infrastructure that can be leveraged in developing the scenarios.
In this project, mapping was performed with the computer software 'QGIS', which analyses and edits spatial information and constructs and exports graphical maps. It has been used to allocate solar and wind resources and for demand projections for each calculated region. Population density, access to electricity, and the distribution of wealth, or the economic development projections, are key input parameters in the region-specific analysis of Costa Rica's future energy situation.

Open-source data and maps from various sources are used to visualize the country and its regions and districts. Further demographic data related to population and poverty, as well as transmission networks and power plants, are also plotted on the maps. The main data sources and assumptions made for this mapping are summarized in the table below.

Table 10: [R]E 24/7—GIS-mapping—data sources

Data	Assumptions	Source
Regions		
Land use/land cover	Land cover types of bare soil, annual cropland, perennial cropland, and grassland are included in the wind analysis. Only land cover types of bare soil, perennial cropland, and open bushland are included in the solar analysis.	World Bank: ESMAP
Elevation	For both wind and solar analyses, any land with a slope of more than 30% was ignored.	Open DEM
Bathymetry	Offshore water bodies (ocean) within 70 km of the coast and with a depth of no more than 50 m below sea level were included in the offshore wind analysis.	GEBCO
Population density	Estimates of numbers of people per pixel (ppp), with national totals adjusted to match UN population division estimates.	WorldPop
Poverty	Based on the GSO-WB poverty headcount in percentage terms for each province.	World Bank
Power plants	The Global Power Plant Database is a comprehensive, open-source database of power plants around the world.	Global Power Plant Database, World Resource Institute
Solar irradiance	The average yearly direct normal insolation/irradiation (DNI) values range from 1 to 5 MWh/m^2 per year.	Solar GIS
Transmission lines and network	Only those sites within 10 km of an existing transmission line were included in the analysis.	EnergyData.info
Wind speed	Wind speeds above 6 m/s were considered at a height of 80 m.	Global wind atlas

The areas of land available for potential solar and wind power generation were calculated at both national and regional levels (seven regions of Costa Rica—see section 3.4) using the ellipsoidal area tool in the *QGIS* processing toolbox. Intersects were created between the transmission level layers and the solar/wind utility vector layers to break down the total land area available clusterwise. A correction was made for sites that intersected the cluster boundaries and were part of the two transmission levels. This input was fed into the calculations for the [R]E 24/7 model, as described below.

1.2 LONG-TERM SCENARIO MODELLING

Historically, heating, electricity, and mobility have been separated in terms of their energy sources, requiring different infrastructures and therefore different planning: electricity for stationary power, petrol and diesel for mobility, and onsite heat for buildings and industrial processes. This will almost certainly change, with increasing use of electricity for heating and mobility, such as in electric vehicles. This emerging *sector coupling* must be considered and requires an integrated approach across heat, mobility, and electricity/stationary power when developing future energy system scenarios, as is done in this model.

Three scenarios have been developed, a reference scenario and two alternative energy pathways. The assumptions for those scenarios are documented in section 3.7. The long-term (LT) modelling approach used in this research is based on the development of target-orientated scenarios. In this approach, a target is set and technical scenarios are developed to meet this target, and then compared with a reference scenario. The set target can be expressed in terms of annual emissions and/or renewable energy shares. For Costa Rica, an exogenous target of a coal phase-out by 2025 (see section 3.7.1) has been taken into account for all scenarios. The scenarios are based on detailed input datasets that consider defined targets, renewable and fossil fuel energy potentials, and specific parameters for power, heat, and fuel generation in the energy systems. The datasets are then fed into LT-[R]E 247, which is based on a DLR model that uses the MESAP/PlaNet software, an accounting framework, to calculate the complete energy system balance to 2050.

The LT-[R]E 24/7 model simulation consists of two independent modules:

1. a flow calculation module, which balances energy supply and demand annually; and
2. a cost calculation module, which calculates the corresponding generation and fuel costs.

Note that this is not a dispatch model, such as the [R]E 24/7 power sector model used to calculate future regional and hourly power, or a technical grid simulation (including frequency stability), such as DIgSILENT's PowerFactory, which is beyond the scope of this analysis.

The LT-[R]E 24/7 model is a bottom-up integrated energy balance model. Different modelling approaches each have their benefits and drawbacks. This model is particularly good in helping policy makers and analysts understand the relationships between different energy demand types in an economy—across all sectors and over a long time period, usually 30–40 years. In a simulation model, the user specifies the drivers of energy consumption, including the forecast population growth, GDP, and energy intensities.

Specific energy intensities are assumed for:

- electricity consumption per person;
- the ratio of industrial electricity and heat demand intensity to GDP;
- demand intensities for energy services;
- energy intensities of different transport modes.

The electricity demand projections for the building and industry sectors are calculated with [R]E 24/7 (see section 4.4) as an input for the LT-[R]E 24/7 model of the alternative scenarios, but not for the REFERENCE scenario, in which they are taken from the ELECTRICAL GENERATION EXPANSION PLAN – 2018–2034 (GEP 2019)[6] (May 2019).

The electricity demand for the transport sector has been calculated with the LT-[R]E 24/7 model. For both heat and electricity production, the model distinguishes between different technologies, which are characterized by their primary energy source, efficiency, and costs. Examples include biomass or gas burners, heat pumps, solar thermal and geothermal technologies, and several power generation technologies, such as photovoltaics, wind, biomass, gas, coal, nuclear, and combined heat and power (CHP).

[6] ELECTRICAL GENERATION EXPANSION PLAN – 2018-2034 (GEP 2019), INSTITUTO COSTARRICENSE DE ELECTRICIDAD, DIRECCION CORPORATIVA DE ELECTRICIDAD PLANIFICACION Y DESARROLLO ELECTRICO, PROCESO EXPANSION DEL SISTEMA,; https://www.grupoice.com/wps/portal/ICE/Electricidad/proyectos-energeticos/planes-de-expansion

For each technology, the market share with respect to the total heat or electricity production is specified based on a range of assumptions, including the renewable energy target, potential costs, and societal, structural, and economic barriers. The main outputs of the model are:

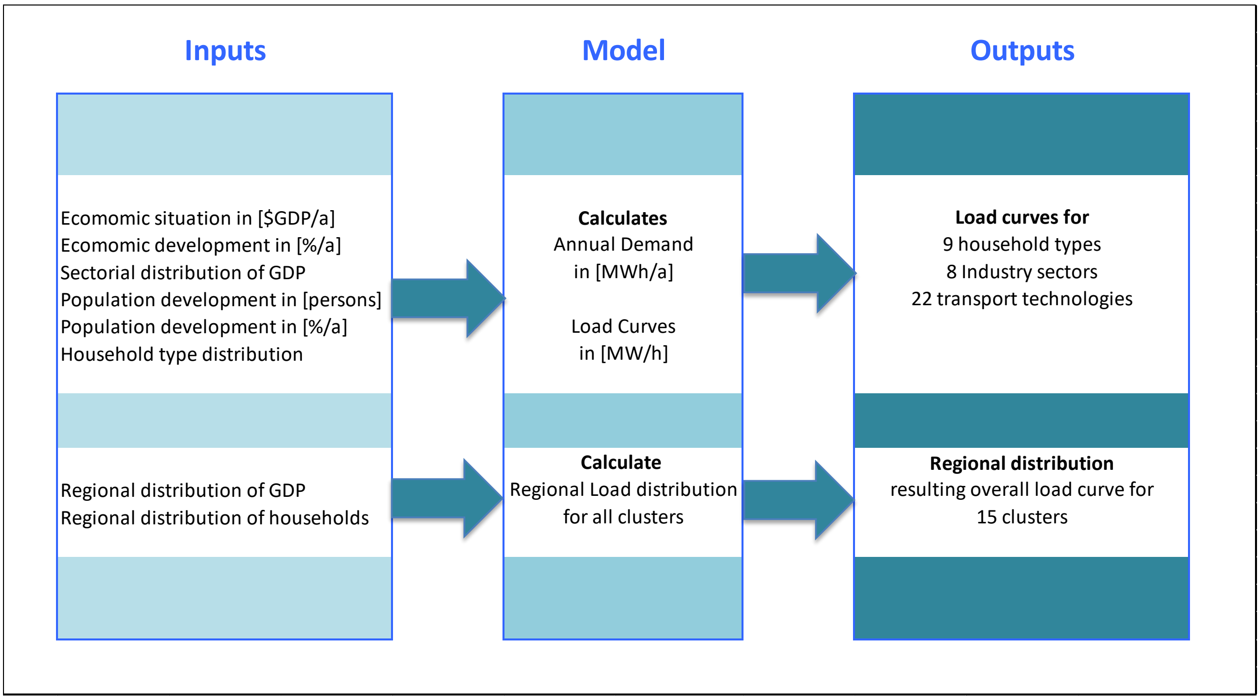
- final and primary energy demand, broken down by fuel, technology, and sector of the economy, as defined by the International Energy Agency (IEA): industry, power generation, transport, and other (buildings, forestry, and fisheries)[7];
- results broken down by the three main types of energy demand—electricity, heating, and mobility (transport); specifically, the energy required, technology deployment, and finance;
- total energy budget, or the total cost of energy for the whole energy system;
- energy-related greenhouse gas emissions over the projection period.

1.3 [R]E 24/7—POWER ANALYSIS

After the geographic analysis and the development of the long-term energy pathways for Costa Rica, the power sector was analysed in a third step with the [R]E 24/7 module.

The energy demand projections and resulting load curve calculations are important factors, especially for power supply concepts with high shares of variable renewable power generation. Calculation of the required dispatch and storage capacities is vital for the security of supply. A detailed bottom-up projection of the future power demand, based on the applications used, demand patterns, and household types, allows a detailed forecast of the demand. Infrastructure needs, such as power grids, combined with storage facilities require an in-depth knowledge of the local loads and generation capacities. However, this model cannot simulate frequencies or ancillary services, which would be the next step in a power sector analysis.

Figure 6: Overview—Energy demand and load curve calculation module



[7] Note that these industry sectors correspond to IEA energy statistics input into the model.

1.3.1 METEOROLOGICAL DATA

Variable power generation technologies are dependent on the local solar radiation and wind regimes. Therefore, all the installed capacities in this technology group are connected to cluster-specific time series. The data were derived from the database *Renewable Ninja* (RE-N DB 2018)[8], which allows the simulation of the hourly power output from wind and solar power plants at specific geographic positions throughout the world. Weather data, such as temperature, precipitation, and snowfall, for the year 2014 were also available. To utilize climatization technologies for buildings (air-conditioning, electric heating), the demand curves for households and services are connected to the cluster-specific temperature time series.

For every region included in the model, hourly output traces are utilized for onshore wind, offshore wind, utility solar, and rooftop solar photovoltaics. Given the number of clusters, the geographic extent of the study, and the uncertainty associated with the prediction of the spatial distribution of future-generation systems, a representative site was selected for each of the five generation types.

Once the representative sites were chosen, the hourly output values for typical solar arrays and wind farms were selected with the database of Stefan Pfenninger (at ETH Zurich) and Iain Stafell (Renewables.ninja; see above). The model methodology used by the Renewables.ninja database is described by Pfenninger and Staffell (2016a and 2016b)[9], and is based on weather data from global reanalysis models and satellite observations (Rienecker and Suarez 2011[10]; Müller and Pfeifroth, 2015[11]). It is assumed that the utility-scale solar sites will be optimized, and as such, a tilt angle was selected within a couple of degrees of the latitude of the representative site. For rooftop solar calculations, this was left at the default 35° because it is likely that the panels will match the roof tilt.

The wind outputs for both onshore and offshore winds were calculated at an 80 m hub height because this reflects the wind datasets used in the mapping exercise. Although onshore wind and offshore wind are likely be higher than this, 80 m was considered a reasonable approximation and made our model consistent with the mapping-based predictions. A turbine model of Vestas V90/2000 was used.

Limitations: The solar and wind resources can differ within one cluster. Therefore, the potential generation output can vary within a cluster and across the model period (2020–2050).

[8] RE-N DB (2018) Renewables.ninja, open database for hourly time series for solar and wind data for a specific geographical position, viewed and data down load took place between May and July 2018, https://www.renewables.ninja/

[9] Pfenninger, S, Staffell, I. (2016a), Pfenninger, Stefan and Staffell, Iain (2016). Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114, pp. 1251-1265. doi: 10.1016/j.energy.2016.08.060

Pfenninger, S, Staffell, I. (2016b), Staffell, Iain and Pfenninger, Stefan (2016). Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, pp. 1224-1239. doi: 10.1016/j.energy.2016.08.068

[10] Rienecker, M, Suarez MJ, (2011) Rienecker MM, Suarez MJ, Gelaro R, Todling R, et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. Journal of Climate, 24(14): 3624-3648. doi: 10.1175/JCLI-D-11-00015.1

[11] Müller, R., Pfeifroth, U (2015), Müller, R., Pfeifroth, U., Träger-Chatterjee, C., Trentmann, J., Cremer, R. (2015). Digging the METEOSAT treasure—3 decades of solar surface radiation. Remote Sensing 7, 8067–8101. doi: 10.3390/rs70608067

1.4 POWER DEMAND PROJECTION AND LOAD CURVE CALCULATION

The [R]E 24/7 Power Analysis model calculates the development of the future power demand and the resulting possible load curves. Actual load curves, particularly for low- and middle-income countries, do not yet exist or are classified, and therefore must be calculated based on a set of assumptions. The model generates annual load curves with hourly resolution and the resulting annual power demands for three different consumer sectors:

- households;
- industry and business; and
- transport.

Although each sector has its specific consumer groups and applications, the same set of parameters is used to calculate the load curves:

- electrical applications in use;
- demand pattern (24 h);
- meteorological data
  - sunrise and sunset, associated with the use of lighting appliances;
  - temperature and rainfall, associated with climatization requirements;
- efficiency progress (base year 2015) for 2020 until 2050, in 5-year steps
  - possibility that the electricity intensity data for each set of appliances will change, e.g., change from CFL light bulbs to LEDs as the main technology for lighting.

Methodology: Load curve calculation for households

The model differentiates nine household groups with various degrees of electrification and equipment:

- Rural – phase 1: Electrified household—basic appliances—low efficiency standard
- Rural – phase 2: All white goods are introduced and increase the overall demand
- Rural – phase 3: Fully equipped standard western household with electrical cooking, air conditioning, and vehicle(s)
- Urban single: Household with basic equipment, low to medium efficiency standard
- Urban shared flat: 3–5 persons share one apartment in urban area; fully equipped western household, but without vehicles
- Urban – family 1: 2 adults and 2–3 children, middle income
- Urban – family 2: 2 adults and > 3 children, and/or higher income
- Suburbia 1: Average family, middle income, full equipment for high transport demand because of extensive commuting
- Suburbia 2: High-income household, fully equipped, extremely high transport demand because of high-end vehicles and extensive commuting.

The following electrical equipment and applications can be selected from a drop-down menu:

- Lighting: 4 different light bulb types
- Cooking: 10 different cooking stoves (2+4 burners, electricity, gas, firewood)
- Entertainment: 3 different computer, TV, and radio types
- White goods: 2 different efficiencies for washing machines, dryers, fridges, freezers
- Climatization: 2 different efficiency levels each for fan, air-conditioning
- Water heating: a selection of direct electric, heat pump, and solar

For details of the household demand projections and categories developed for the Costa Rica analysis, see section 3.2.

Load curve calculation for business and industry

The industrial sector is clustered into eight groups based on widely used statistical categories:

- Agriculture
- Manufacturer
- Mining
- Iron and steel
- Cement industry
- Construction industry
- Chemical industry
- Service and trade

For each sector, 2–6 different efficiency levels are available. The data are taken from international statistical publications (IEA [2016][12], IRENA [2016][13], DLR [2012][14]).

For the Costa Rica modelling project, the business and industry load curve calculations were simplified according to the limited data availability and to make our calculations comparable to those of ELECTRICAL GENERATION EXPANSION PLAN–2018–2034 (GEP 2019)[6]. The demand and load curve calculations for industry and business are based on the following three economic sectors:

- Agriculture
- Industry and construction
- Service and trade

Thus, the industry-specific projections for *manufacturing*, *mining*, *iron and steel*, *cement industry*, *construction industry*, and the *chemical industry* are summed into one demand and one resulting load curve. For industry, the base load is assumed, whereas for agriculture and service & trade, core working hours from 6 am to 8 pm are assumed.

[12] IEA (2016), World Energy Balances, 2016

[13] Report citation IRENA (2016), REmap: Roadmap for a Renewable Energy Future, 2016 Edition. International Renewable Energy Agency (IRENA), Abu Dhabi, www.irena.org/remap

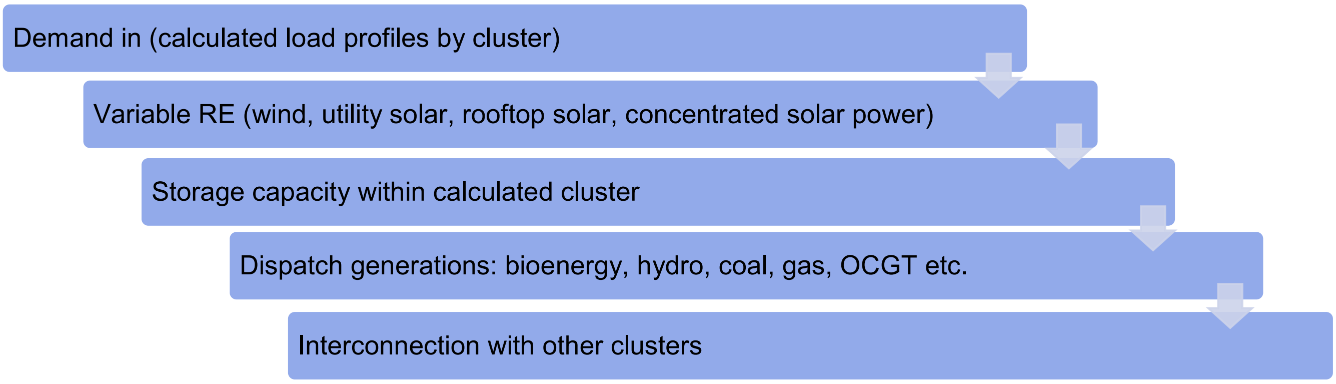
[14] DLR et. al. (2012) Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global Schlussbericht BMU - FKZ 03MAP146 (DLR), (IWES), (IFNE), 29 March 2012

1.5 THE [R]E 24/7 DISPATCH MODULE

The [R]E 24/7 dispatch module simulates the physical electricity supply with an interchangeable cascade of different power generation technologies. The cascade starts with the calculated load in megawatts for a specific hour. The first generation technology in the exogenous dispatch order provides all the available generation, and the remaining load is supplied by the second technology until the required load is entirely met. In the case of oversupply, the surplus variable renewable electricity can be either moved to storage, moved to other regions, or—if neither option is possible—curtailed. Non-variable renewable sources reduce output. In the case of undersupply, electricity is supplied either from available storage capacities, from neighbouring clusters, or from dispatch power plants. The key objective of the modelling is to calculate the load development by region, changing the residual loads (load minus generation), theoretical storage, and interconnection requirements for each cluster and for the whole survey region. The theoretical storage requirement is provided as "storage requirement to avoid curtailment". The economic battery capacity is a function of the storage and curtailment costs, as well as the dispatch power plant availability and costs. This analysis requires detailed local technical parameters, which were not available for this analysis.

Figure 5 provides an overview of the dispatch calculation process. The dispatch order can be changed in terms of the order of renewables and the dispatch power plant, as well as in the order of the generation categories: variable, dispatch generation, and storage. The following key parameters are used as input: generation capacity by type, demand projection and load curve for each cluster, interconnection with other clusters, and meteorological data from which to calculate solar and wind power generation with hourly resolution. The installed capacities are derived from the long-term projections described in section 4.4, and the resulting annual generation in megawatt hours is calculated on the basis of meteorological data (in cases of solar and wind power) or dispatch requirements.

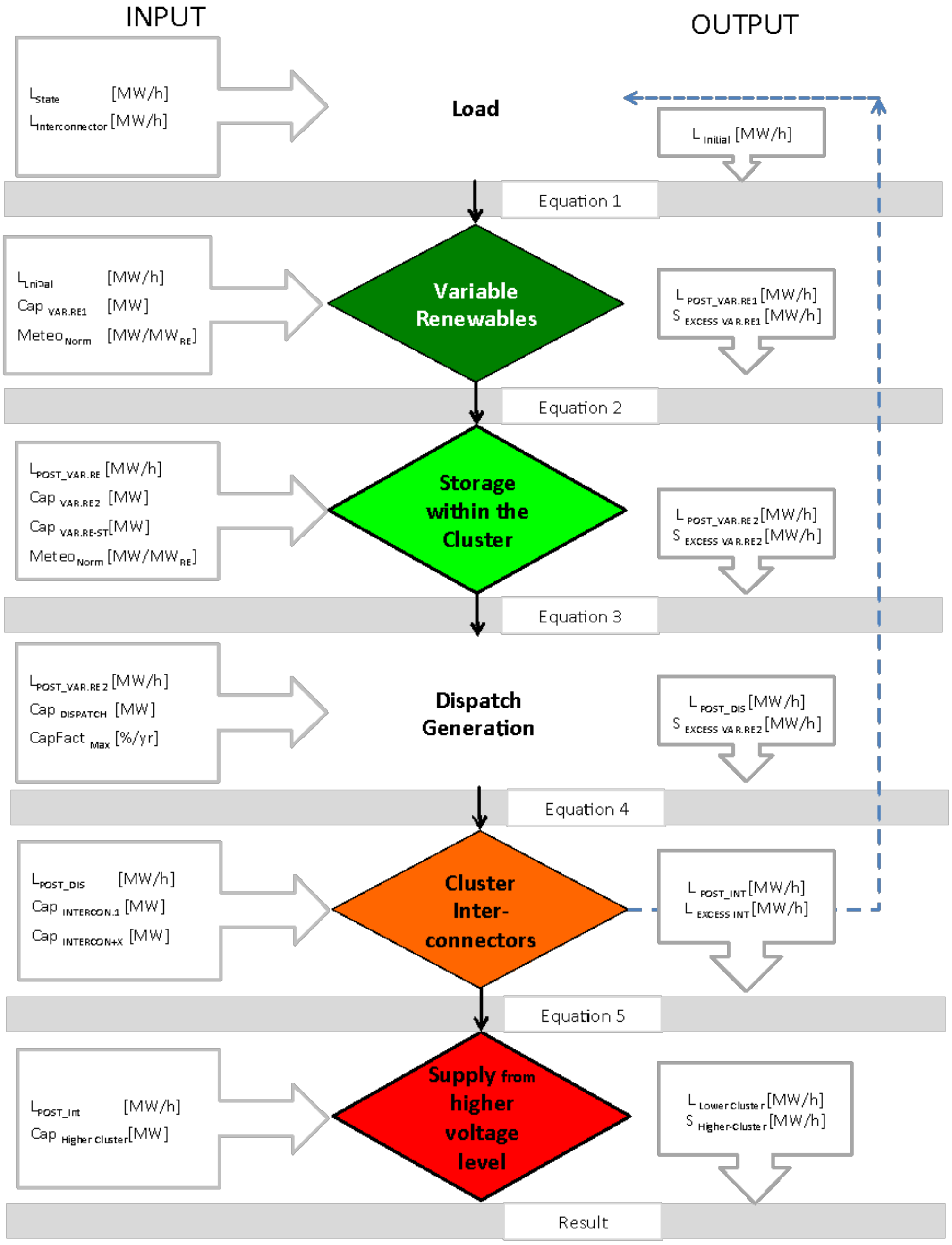
Figure 7: Dispatch order within one cluster



Overview: input and output—[R]E 24/7 energy dispatch model

Figure 6 gives an overview of the input and output parameters and the dispatch order. Although the model allows changes in the dispatch order, a 100% renewable energy analysis always follows the same dispatch logic. The model identifies excess renewable production, which is defined as the potential wind or solar photovoltaic generation that exceeds the actual hourly demand in MW during a specific hour. To avoid curtailment, the surplus renewable electricity must be stored with some form of electrical storage technology or exported to a different cluster. Within the model, excess renewable production accumulates through the dispatch order. If storage is present, it will charge the storage within the limits of the input capacity. If no storage is included, this potential excess renewable production is reported as 'potential curtailment' (pre-storage). It is assumed that a certain number of behind-the-meter consumer batteries will be installed, independent of the system requirements.

Figure 8: Overview—Input, output, and dispatch order



2 COSTA RICA: SCENARIO ASSUMPTIONS

2.1 POLITICAL CONTEXT

Costa Rica is a constitutional democratic republic with a multi-party system. Executive power resides with the President, while legislative powers are vested in the Legislative Assembly. Costa Rica is one of the most prosperous and politically stable countries in the region and is the only Central American state without a permanent standing army, after it was abolished in 1949. In March 2018, the centre-left candidate Carlos Alvarado won the presidential election by a wide margin of around 20%.[15] The Government has indicated that stimulating economic growth, reducing unemployment (which in the second quarter of 2019 rose to 11.9%, one of the highest figures in recent years), and decarbonizing the economy are among its key priorities.[16]

2.2 SOCIAL CONTEXT

Costa Rica is characterized by political stability, a high standard of living, and a well-developed social benefits system, which sets it apart from many of its Central American neighbours. Through the commitment of successive governments to substantial social spending (almost 20% of GDP annually), Costa Rica has made significant progress in areas such as the provision of universal access to education, healthcare, clean water, sanitation, and electricity.[17] Social cohesion, political stability, and steady economic growth have resulted in one of the lowest poverty rates in Latin America.[18] With most of the population living in urban areas[5], the majority of Costa Rica's poor people are situated in rural areas, where there is a lack of resources, jobs and opportunities. While 20% of the population lives below the national poverty line ($155 per month), only 2% live below the international poverty line.[19] Initiatives such as the "Puente del Desarrollo" ("Bridge of Development") aim to combine social initiatives and projects into one bigger program to reduce poverty and rising inequalities.[20]

Despite continuous GDP growth from $37.3 billion in 2010 to around $60 billion in 2018[21], Costa Rica's unemployment rate has risen from 9.7% in July 2016 to 11.9% in July 2019, one of the highest figures in recent years.[22] As far as education standards are concerned, Costa Rica's literacy rate stands at 97.86%, one of the highest of all Latin American countries, and a majority of the population speaks English, mainly as a result of Costa Rica's tourism industry.[23] Public education is guaranteed in the constitution and both pre- and high-school education have been free since 1869.[24]

2.3 ECONOMIC CONTEXT

Costa Rica is considered to be an upper middle-income country (MIC).[25] The GDP per capita in Costa Rica was last recorded at $12,0272 in 2018, which is more than triple its value 30 years ago.[26] The country's steady growth over the last decades has been credited to an outward-oriented strategy, based on an openness to foreign investment and gradual trade liberalization. Costa Rica's inflation rate fell to 2.86% in August 2019, which increased its annual average inflation from 2.1% to 2.2%.[27]

Costa Rica's commodity-driven economy is led by traditional agricultural exports of bananas, coffee, sugar and beef. Agriculture makes up around 5%–6% of GDP[28] and employs around 12.5% of the labour force.[29] Tourism is another key sector of the economy, representing around 8% of the country's GDP and creating some 156,000 jobs.[30] Costa Rica is also an exporter of medical devices and other high-value-added goods and services. Increasing investment in high-level technologies over the past years have driven GDP growth considerably, particularly in the greater metropolitan area of San José. Whereas high-level technologies could enable Costa Rica to leapfrog certain soon-to-be-obsolete technologies, it also requires a highly qualified labour force. This excludes the larger part of the population outside the San José metropolitan region who have neither the knowledge nor the skills to participate in this sector.

[15] https://www.bbc.com/news/world-latin-america-43614744
[16] https://ticotimes.net/2019/09/02/government-will-present-plan-hoping-to-spark-costa-ricas-economic-growth
[17] https://www.cia.gov/library/publications/the-world-factbook/geos/print_cs.html
[18] https://www.worldbank.org/en/country/costarica/overview
[19] https://borgenproject.org/poverty-in-costa-rica-2/
[20] Ibid.
[21] https://data.worldbank.org/country/costa-rica
[22] https://www.centralamericadata.com/en/article/home/Costa_Rica_Unemployment_Rate_Goes_Up_to_119
[23] http://uis.unesco.org/en/country/cr
[24] https://thecostaricanews.com/costa-rican-educational-system/
[25] https://www.worldbank.org/en/country/costarica
[26] https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=CR
[27] https://www.focus-economics.com/country-indicator/costa-rica/inflation
[28] https://data.worldbank.org/indicator/NV.AGR.TOTL.ZS?locations=CR
[29] https://www.statista.com/statistics/454908/employment-by-economic-sector-in-costa-rica/
[30] https://qcostarica.com/costa-rica-tourism-shines-despite-a-slow-world-economy/

As part of implementing its National Plan for Development and Public Investments (2019–2022)[31], the Government announced in September 2019 a public investment package of $9.526 billion dollars to boost the economy and reduce unemployment. The Ministry of Planning and Economic Policy specified that this investment will go to road, educational, airport, and hospital infrastructure projects, as well as energy, health, safety, and justice projects.[32]

2.4 SOCIO-ECONOMIC PARAMETERS

Projections of population and economic growth are important factors in building energy scenarios because they affect the size and composition of the energy demand, both directly and through their impact on economic growth and development.

The current population of Costa Rica is 5 million, up from 4.58 million at the 2011 census. This makes Costa Rica the 120th most populous country in the world. Population growth has been steady at around 1% per year, and 80% of the country's population live in a city or a surrounding urban area. The capital and largest city is San Jose, which has a population of about 335,000 and a high population density of 6,455 people per square kilometre. The greater metropolitan area has 2.15 million residents or a third of the country's entire population. In 2018, the life expectancy at birth of Costa Ricans was 79.8 years, ranking the country 29th in the world in terms of longevity.

According to projections[33], the population of Costa Rica will grow by 4% per year until 2025, reaching 5.25 million people. The population growth is estimated to slow to around 3% by 2030 and to 1.5% by 2040. Based on these estimates, the population will increase to 5.76 million by 2050 (see Table 11). For the development of the energy scenario, it is assumed that Costa Rica's economic development will grow by 2.75% per year until 2035 and by 2% until 2050.

Table 11: Costa Rica—Population and GDP projections

	t	2017	2020	2025	2030	2035	2040	2045	2050
GDP	[billion US$$_{2010}$/a]	58.2	63	72	82	94	104	115	127
GDP/Person	[US$/capita]	11,867	12,438	13,696	15,200	16,987	18,416	20,081	22,022
Population	[million]	4.902	5.044	5.246	5.413	5.548	5.650	5.721	5.759
			2017–2020	**2020–2025**	**2025–2030**	**2030–2035**	**2035–2040**	**2040–2045**	**2045–2050**
Economic growth	[%/a]		2.75%	2.75%	2.75%	2.75%	2.00%	2.00%	2.00%
Population growth	[%/a]		4.7%	4.0%	3.4%	2.7%	2.0%	1.4%	0.8%

2.5 COSTA RICA: ELECTRICITY DEMAND DEVELOPMENT PROJECTION

The electricity demand projections documented in this section were calculated for the residential and business sectors with the [R]E 24/7 model in a bottom-up process. The further electricity demand entailed by transport (especially under the two alternative scenarios, with increased electric mobility) and by the internal electricity demand of power plants ("own consumption") and the distribution losses are calculated with the long-term model (see sections 2.2 and 4.2) and added to the calculated demand projections. However, the [R]E 24/7 power analysis only takes into account the additional electricity demand for distribution losses because the power plant consumption does not influence the storage or grid requirements.

31 https://observatorioplanificacion.cepal.org/sites/default/files/plan/files/Costa%20Rica%20PNDIP%20%202019-2022.pdf
32 https://ticotimes.net/2019/09/07/costa-rica-announces-multi-million-dollar-investment-to-stimulate-economy-and-jobs
33 The Population Pyramid, Online database, viewed September 2019, https://www.populationpyramid.net/costa-rica/2050/

DEMAND PROJECTIONS FOR THE INDUSTRY AND BUSINESS SECTORS

The industry and business demand development is based on the GDP breakdown (Table 12). It assumes that the overall structure of the economy does not change and that all sectors grow at rates equal to that of GDP over the entire modelling period. Table 13 shows the assumed breakdown of GDP by sub-category. The shares are based on CIA (2019)[34].

Table 12: Development of GDP shares by industry sector across all regions of Costa Rica (2017)

Industry	20.5%
Manufacturing	10.0%
Mining	2.0%
Iron + Steel	1.0%
Cement	1.0%
Construction	5.5%
Energy intensive industry	1.0%
Services	73.5%
Offices & services	65.5%
Tourism	8.0%
Agriculture	6%
Agriculture	6%

The GDP distribution by region is based on 2017 data and is assumed to remain the same for the entire modelling period, until 2050. In the industry sector, an efficiency gain of 0.5% per year has been calculated between 2020 and 2030 and 0.75% per year between 2031 and 2050. In the service and agricultural sectors, an efficiency development of 0.5% per year until 2030 has been calculated, with 0.25% for the rest of the modelling period.

Table 13: Development of Costa Rica's shares of GDP by region

Region	[%]
Alajuela	20%
Cartago	11%
Guanacaste	8%
Heredia	10%
Limon	9%
Puntarenas	10%
San Jose	33%

[34] CIA 2019, Central Intelligence Agency, The World Factbook, Central America / Costa Rica, Page last updated October 24, 2019, https://www.cia.gov/library/publications/the-world-factbook/geos/cs.html

COSTA RICA—ELECTRICITY DEMAND PROJECTIONS—HOUSEHOLDS

The residential sector is the principal consumer with a 40% share of the total electricity consumption in the country. The final use of electricity by kitchen appliances, such as refrigeration and cooking, will account for the majority of household consumption. However, increasing demand for home entertainment and air conditioning will lead to an increasing electricity demand.

Table 14: Distribution of residential electricity consumption in 2018[35]

Electricity consumption	% of final electricity use
Refrigeration	31.5%
Entertainment	16.8%
Cooking	15.5%
Water heating	14.3%
Lighting	11.4%
Washing	4.1%
Climatization	3.5%
Others	3.3%

Electricity demand has been rising by 1.9% on average since 2008.[36] Ensuring that the rising demand is met with renewable energy sources has been the goal of successive governments.

The analysis of the current and future development of the electricity demand for Costa Rica's households is based on a workshop organized in Costa Rica with multiple stakeholders from government, utilities, and the local civil society. The results of this consultation have been used as the input data for future energy demand projections. The different demand levels of households by region were converted into the nine household types. The assumed annual demand in kilowatt-hours per year for each household type is shown Table 15. Significant increases in demand, e.g., from *"Rural Phase 2"* to *"Rural Phase 3"*, are mainly attributed to the use of electrical air-conditioning. The average efficiency gain across all appliances is assumed to be 0.75% per year across the entire modelling period.

Table 15: Household types used in both RENEWABLES scenarios and their assumed annual electricity demands

Household Type			2020 [kWh/a]
Rural – Phase 1	-	Low-income rural household	1,750
Rural – Phase 2	-	Lower-middle-income rural household	3,000
Rural – Phase 3	-	Upper-middle-income rural household	3,200
Urban – Single	-	Very-low-income urban household	1,200
Urban/Shared App.	-	Lower-middle-income urban household	2,400
Urban – Family 1	-	Middle-income-household (urban and rural)	3,000
Urban – Family 2	-	Upper-middle-income urban household	2,500
Suburbia 1	-	High-income rural household	4,500
Suburbia 2	-	High-income urban household	3,500

The estimated development of the country-wide electricity shares in the various household types is presented in Table 16. It is assumed that the income level will increase and therefore that the shares of low-income households will decrease in all three regions (rural, urban, and suburban). The development of the electricity demand for households has been discussed with various stakeholders and assumptions were presented at a workshop in San Jose in October 2019 organised by '*La Ruta del Clima'* and the *World Future Council*.

[35] https://news.co.cr/costa-rica-surpasses-98-of-clean-energy-generation/76502/
[36] https://www.iea.org/countries/Costa%20Rica/

Table 16: Household types—changes in electricity shares countrywide

Household Type	Countrywide Share [%] (rounded)			
	2020	2030	2040	2050
No access to electricity	0%	0%	0%	0%
Rural – Phase 1	22.5%	25.0%	27.5%	25.0%
Rural – Phase 2	17.5%	15.0%	10.0%	7.5%
Rural – Phase 3	5.0%	5.0%	7.5%	12.5%
Urban – Single	10.0%	7.5%	5.0%	2.5%
Urban/Shared App.	10.0%	12.5%	12.5%	15.0%
Urban – Family 1	10.0%	7.5%	10.0%	7.5%
Urban – Family 2	5.0%	7.5%	7.5%	10.0%
Suburbia 1	10.0%	7.5%	5.0%	2.5%
Suburbia 2	10.0%	12.5%	15.0%	17.5%
Total	100%	100.0%	100%	100%

Source: Statistical Information, Stakeholder Workshop 2019 and UTS-ISF estimates

The distribution of electricity shares across the household categories can vary regionally. All shares have been rounded and calibrated to the current regional electricity demand. The authors of this report have deliberately chosen a high standard for Costa Rica's households. The projected development of the electricity demand for Costa Rica's households could be lower if all electrical appliances are of the best technical standard available and if electrical climatization is reduced by the use of energy-efficient solar architecture, which would reduce the overall heating and cooling demand.

2.6 TECHNOLOGY AND FUEL COST PROJECTIONS

The parameterization of the model requires that many assumptions be made about the development of the characteristic technologies, such as the specific investment required and fuel costs. Therefore, because long-term projections are highly uncertain, we must define plausible and transparent assumptions based on background information and up-to-date statistical and technical information.

BACKGROUND: FUEL PRICE PROJECTIONS

The speed of an energy system transition depends, to some extent, on overcoming economic barriers. These largely relate to the relationships between the costs of renewable technologies and those of their fossil and nuclear counterparts. For our scenarios, the projection of these costs is vital, allowing valid comparisons of energy systems to be made. However, there have been significant limitations to these projections in the past in terms of investment and fuel costs. Moreover, efficiency measures also generate costs, which are usually difficult to determine, and depend on the technical, structural, and economic boundary conditions.

During the last decade, fossil fuel prices have seen huge fluctuations. Figure 9 shows the oil prices since 1997. After extremely high oil prices in 2012, we are currently in a low-price phase. Gas prices saw similar development (IEA 2017)[37]. Consequently, fossil fuel price projections have also seen considerable variations (IEA 2017[74]; IEA 2013[38]), and have considerably influenced scenario results ever since, especially those scenarios that are based on cost optimization algorithms.

Although oil-exporting countries have provided the best oil price projections in the past, institutional price projections have become increasingly accurate, with the International Energy Agency (IEA) leading the way in 2018 (Roland Berger 2018)[39]. An evaluation of the oil price projections of the IEA since 2000 by Wachtmeister et al. (2018)[40] showed that price projections have varied significantly over time. Whereas the IEA's oil production projections seem comparatively accurate, oil price projections have shown errors of 40%–60%, even when made for only 10 years ahead. Between 2007 and 2017, the IEA price projections for 2030 varied from \$70 to \$140 per barrel, providing significant uncertainty regarding future costs in the scenarios. Despite this limitation, the IEA provides a comprehensive set of price projections. Therefore, we based our scenario assumptions on these projections, as described below.

Because most renewable energy technologies provide energy with no fuel costs, the projections of investment costs become more important than the fuel cost projections, which limits the impact of errors in the fuel price projections. It is only for biomass that the cost of feedstock remains a crucial economic factor for renewables. Today, these costs range from negative costs for waste wood (based on credit for the waste disposal costs avoided), through inexpensive residual materials, to comparatively expensive energy crops.

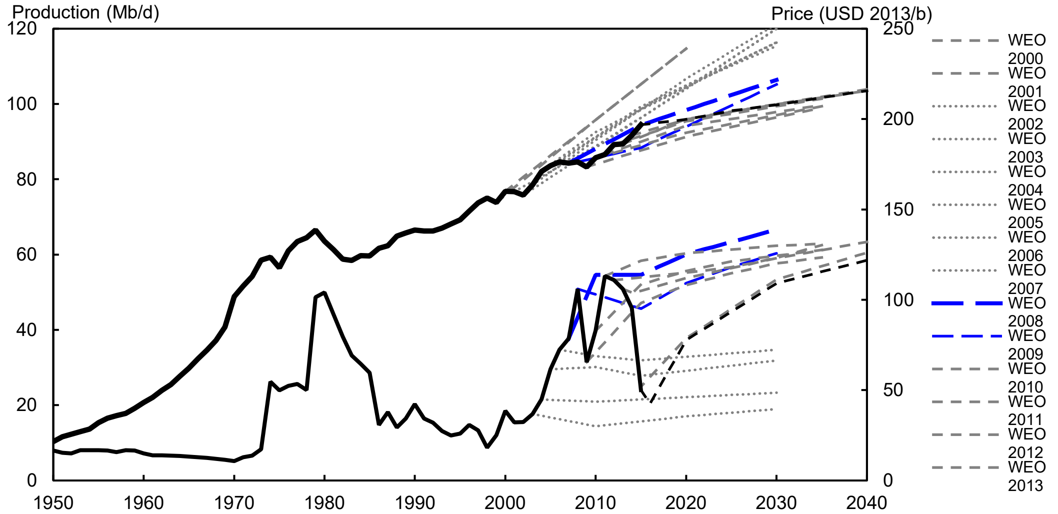


Figure 9: Historic development and projections of oil prices
by IEA according to Wachtmeister et al. (2018)

[37] IEA (2017): IEA (2017) World Energy Outlook 2017. International Energy Agency, Organization for Economic Co-operation and Development, Paris
[38] IEA 2013: IEA (2013) World Energy Outlook 2013. International Energy Agency, Organization for Economic Co-operation and Development, Paris
[39] Roland Berger (2018) 2018 oil price forecast: who predicts best? Roland Berger study of oil price forecasts. https://www.rolandberger.com/en/Publications/pub_oil_price_forecast_2015.html. Accessed 10.9.2018 2018
[40] Wachtmeister H, Henke P, Höök M (2018) Oil projections in retrospect: Revisions, accuracy and current uncertainty. Applied Energy 220:138-153. doi:https://doi.org/10.1016/j.apenergy.2018.03.013

The projection of investment cost also poses challenges for scenario development. Available short-term projections of investment costs depend largely on the data available for existing and planned projects. Learning curves are most commonly used to assess the future development of investment costs as a function of their future installations and markets (McDonald and Schrattenholzer 2001[41]; Rubin et al. 2015[42]). Therefore, the reliability of cost projections largely depends on the uncertainty of future markets and the availability of historical data. Fossil fuel technologies provide a large cost dataset, featuring well-established markets and large annual installations. They are also mature technologies, where many potential cost reductions have already been exploited.

For renewable technologies, the picture is more mixed. For example, hydro power is (like fossil fuels) well established and provides reliable data on investment costs. Other technologies, such as solar photovoltaic and wind, are currently experiencing tremendous advances in installation and cost reduction. Photovoltaic and wind power are the focus of cost monitoring, and considerable data are already available on existing projects. However, their future markets are not easily predicted, as can be seen from the evolution of IEA market projections over recent years in the World Energy Outlook series (compare, for example, IEA 2007, IEA 2014, and IEA 2017). For photovoltaic and wind energy, small differences in cost assumptions will lead to large deviations in the overall costs, so cost assumptions must be made with especial care.

Furthermore, many technologies feature only relatively small markets, such as geothermal and modern bioenergy applications, for which costs are still high and for which future markets are insecure. The cost reduction potential is correspondingly high for these technologies. This is also true for technologies that might become important in a transformed energy system but are not yet widely available. Hydrogen production, ocean power, and synthetic fuels might deliver important technological options in the long term after 2035, but their cost reduction potential cannot be assessed with any certainty today.

Therefore, cost assumptions are a crucial factor in evaluating scenarios. Because costs are an external input into the model and are not calculated internally, we have assumed the same progressive cost developments for all scenarios. In the next section, we present a detailed overview of our assumptions for power and renewable heat technologies, including the investment and fuel costs and the potential CO_2 costs, in the various scenarios.

POWER AND COMBINED HEAT AND POWER (CHP) TECHNOLOGIES

The focus of cost calculations in our scenario modelling is the power sector. We compare the specific investment costs estimated in previous studies (Teske et al. 2019[43] and Teske et al. 2015[44]), which were based on a variety of studies, including investment cost projections by the IEA (IEA 2014) and current cost assumptions by IRENA and IEA (IEA 2016c). We found that the investment costs generally converged, except for the cost of solar photovoltaic, which was higher than average.

The cost projections for power plant and co-generation technologies are taken from Teske et al. (2019)[43]. = To achieve results comparable to INEC (2018) (for the baseline scenario) fuel costs have been taken from INEC (2018)[6]. The technology costs (overnight costs and escalation costs due to the interest rates during construction) are given in Table 16. A discount rate of 10% was used for the cost of capital. This discount rate was used to calculate the investment annuities and the levelized costs of electricity over the technical lifetime of the power plant.

Several renewable technologies have seen considerable cost reductions over the last decade. This is expected to continue if renewables are extensively deployed. Fuel cells are expected to outpace other CHP technologies, with a cost reduction potential of more than 75% (from currently high costs). Hydro power and biomass will remain stable in terms of costs. Tremendous cost reductions are still expected for solar energy and offshore wind, even though they have experienced significant reductions already. However, photovoltaic costs could drop to 35% of today's costs. Offshore wind has experienced significant cost reductions over the past decade, and could drop a further 30% over the next decade, whereas the cost reduction potential for onshore wind seems to have been exploited to a large extent already. The investment costs provided in the table below are only the technology costs, and exclude the costs for operation and maintenance and the land fuel costs.

[41] McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. Energy Policy 29 (4):255-261. doi:https://doi.org/10.1016/S0301-4215(00)00122-1
[42] Rubin ES, Azevedo IML, Jaramillo P, Yeh S (2015) A review of learning rates for electricity supply technologies. Energy Policy 86:198-218. doi:https://doi.org/10.1016/j.enpol.2015.06.011
[43] Teske (2019), Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2.0°C, ISBN 978-3-030-05842-5, Springer, Switzerland 2019
[44] Teske S, Sawyer S, Schäfer O, Pregger T, Simon S, Naegler T, Schmid S, Özdemir ED, Pagenkopf J, Kleiner F, Rutovitz J, Dominish E, Downes J, Ackermann T, Brown T, Boxer S, Baitelo R, Rodrigues LA (2015) Energy [R]evolution - A sustainable world energy outlook 2015. Greenpeace International

Table 17: Investment cost assumptions for power generation plants (in US$/kW) until 2050

Assumed Investment Costs for Power Generation Plants						
		2017	2020	2030	2040	2050
Coal power plant	$/kW	1,816	1,816	1,816	1,816	1,816
Lignite power plant	$/kW	1,998	1,998	1,998	1,998	1,998
Gas power plant	$/kW	608	454	454	454	608
Oil power plant	$/kW	863	845	808	781	745
Diesel generator	$/kW	817	817	817	817	817
Nuclear power plant	$/kW	5,993	5,449	4,631	4,086	4,086
Co-Generation–fossil						
CHP coal	$/kW	1,456	1,456	1,456	1,456	1,456
CHP gas	$/kW	510	510	510	510	510
CHP lignite	$/kW	1,456	1,456	1,456	1,456	1,456
CHP oil	$/kW	957	937	899	861	823
Renewables						
Biomass power plant	$/kW	2,179	2,134	2,089	1,998	1,916
Hydro power plant	$/kW	4,200	4,200	4,100	4,100	4,100
Wind turbine offshore	$/kW	2,200	2,100	1,371	1,317	1,271
Wind turbine onshore	$/kW	3,632	3,351	2,897	2,570	2,370
Photovoltaic, rooftop	$/kW	1,418	1,181	663	509	427
Photovoltaic—utility scale	$/kW	1181	890	663	509	427
Geothermal power plant	$/kW	7,700	7,700	7,500	6,600	6,500
CSP power plant (incl. storage)	$/kW	5,176	4,540	3,360	2,770	2,488
Ocean energy power plant	$/kW	6,311	6,039	3,996	2,815	1,916
Hydrogen production	$/kW	1253	1108	835	636	518
Co-Generation–renewable						
CHP biomass	$/kW	1,820	1,784	1,747	1,675	2,460
CHP fuel cell	$/kW	4540	4540	2270	2270	1017
CHP geothermal	$/kW	9,610	8,147	6,476	5,432	4,700

*Costs for a system with a solar multiple of two and thermal storage for 8 h of turbine operation
**Values apply to both run-of-the-river and reservoir hydro power

HEATING TECHNOLOGIES

Assessing the costs in Costa Rica's industrial heating sector is even more ambitious than estimates in the power sector. The costs of new installations differ significantly between regions and are linked to construction costs and industry processes, which are not addressed in this study. Moreover, no data were available to allow the comprehensive calculation of the costs of existing heating appliances in Costa Rica. Therefore, we concentrate on the additional costs that will result from the application of new renewable resources in the heating sector. Our cost assumptions for heat generation are based on a previous survey of renewable heating technologies across Europe, which focused on solar collectors, geothermal energy, heat pumps, and biomass applications. Biomass and simple heating systems in the residential sector are already mature. However, more-sophisticated technologies, which can provide higher shares of the heat demand from renewable sources, are still under development and rather expensive. Market barriers will slow the further implementation and cost reduction of renewable heating systems, especially for heating networks. Nevertheless, significant learning rates can be expected if renewable heating is increasingly implemented, as projected in our high-renewables scenarios.

Table 17 presents the investment cost assumptions for heating technologies in Europe, disaggregated by sector. Geothermal heating displays the same high costs in all sectors. In Europe, deep geothermal applications are being developed for heating purposes at investment costs ranging from $500 per kilowatt thermal [$/kW$_{thermal}$] (shallow) to $ 3000/kW$_{thermal}$ (deep), and the costs are strongly dependent on the drilling depth. The cost reduction potential is assumed to be around 30% by 2050 (Teske et al. 2019)[7].

Table 18: Specific investment cost assumptions (US$/kW) for heating technologies in all scenarios until 2050

Investment costs for heat-generation plants in OECD Europe							
			2017	**2020**	**2030**	**2040**	**2050**
Geothermal		$/kW	2170	2061	1843	1635	1444
Heat pumps		$/kW	1625	1580	1489	1398	1300
Biomass heat plants		$/kW	545	527	499	463	436
Residential biomass stoves	Industrialized countries	$/kW	763	736	690	654	620
Residential biomass stoves	Developing countries	$/kW	100	100	100	100	100
Solar collectors	Industry	$/kW	772	745	663	590	500
	In heat grids	$/kW	881	881	881	881	881
	Residential	$/kW	963	917	826	726	600

Heat pumps typically provide hot water or space heat for heating systems at relatively low supply temperatures, or they supplement other heating technologies. Therefore, they are currently mainly used for small-scale residential applications. Costs currently cover a large bandwidth and are expected to decrease by only 20% to around $1300/kW by 2050 (Teske et al. 2019)[7]. For biomass and solar collectors, we assume the appropriate differences between the sectors. There is a broad portfolio of modern technologies for heat production from biomass, ranging from small-scale single-room stoves to heating or CHP plants on a megawatt scale.

Investment costs show similar variations: simple log-wood stoves can cost from $100 per kilowatt, but more sophisticated automated heating systems that cover the whole heat demand of a building are significantly more expensive. Log-wood or pellet boilers range from $500/kW to $1300/kW. Large biomass heating systems are assumed to reach their cheapest in 2050 at around $700/kW for industry.
For all sectors, we assume a cost reduction of 20% by 2050. In contrast, solar collectors for households are comparatively simple and will become cheap (at $650/kW) by 2050. The cost of simple solar collectors for swimming pools might have been optimized already, whereas their integration into large systems is neither technologically nor economically mature. For larger applications, especially in heat grid systems, the collectors are large and more sophisticated. Because there is not yet a mass market for such grid-connected solar systems, we assume there will be a cost reduction potential until 2050 (Teske et al. 2019)[7].

FUEL COST PROJECTIONS

Although fossil fuel price projections have seen considerable variations, as described above, we based our fuel price assumptions on INEC (2018)[6] and LAZARDS (2018)[45]. Although these price projections are highly speculative, they provide a set of prices consistent with our investment assumptions. For bioenergy, we assumed fuel supplies from harvesting and process residuals in a price range of $3/GJ to $5/GJ (IRENA 2014)[46]

Table 19: Development projections for fossil fuel prices

Development projections for fossil fuel prices						
All Scenarios		2017	2020	2030	2040	2050
Biomass	$/GJ	7.80	13.80	20.10	26.20	30.60
Oil	$/GJ	6.58	8.80	11.80	13.40	14.50
Gas	$/GJ	12.58	13.60	14.00	14.40	14.80
Coal	$/GJ	1.95	2.21	3.18	3.50	3.80
Nuclear	$/GJ	0.9	0.9	1.1	1.3	1.5

[45] LAZARDS (2018); Lazard's Levelized Cost of Energy Analysis—Version 12.0, November 2018
[46] IRENA (2014), Global Bioenergy Supply and Demand Projections: A working paper for Remap 2030, International Renewable Energy Energy Agency, Abu Dhabi, United Arab Emirates

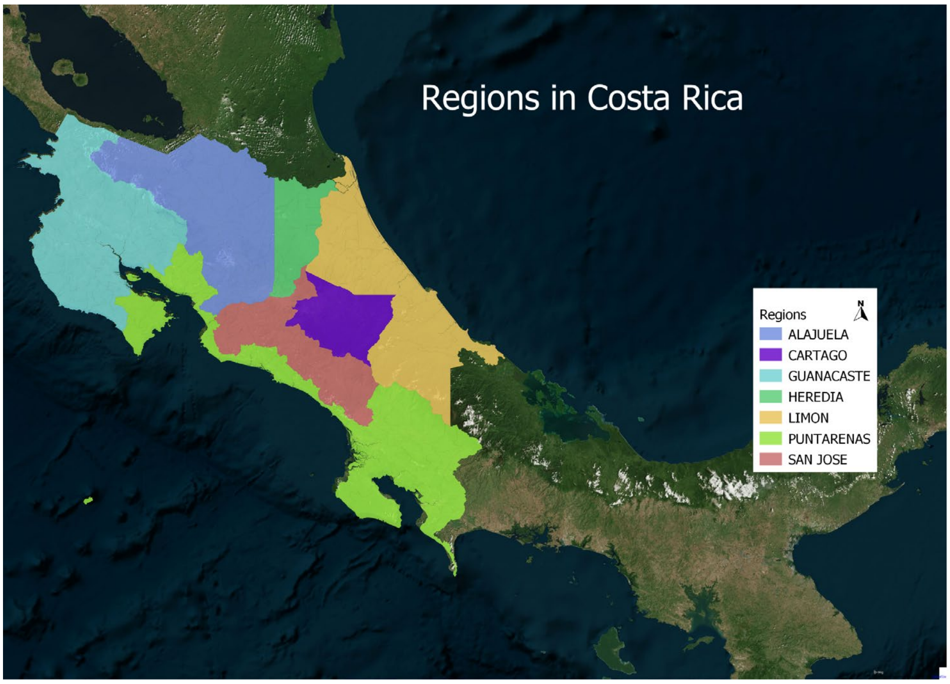
2.7 COSTA RICA: GEOGRAPHIC INFORMATION

The regional distribution of the population and the availability of energy infrastructure correlate with the socio-economic situation in Costa Rica and its future economic development, with the exception of high-level tourism in national park areas. The following maps provide an overview of Costa Rica's regional population, the locations of power lines and power plants, a regional breakdown of the energy pathways, and a power sector analysis (section 5.9).

Distribution of population and power grid

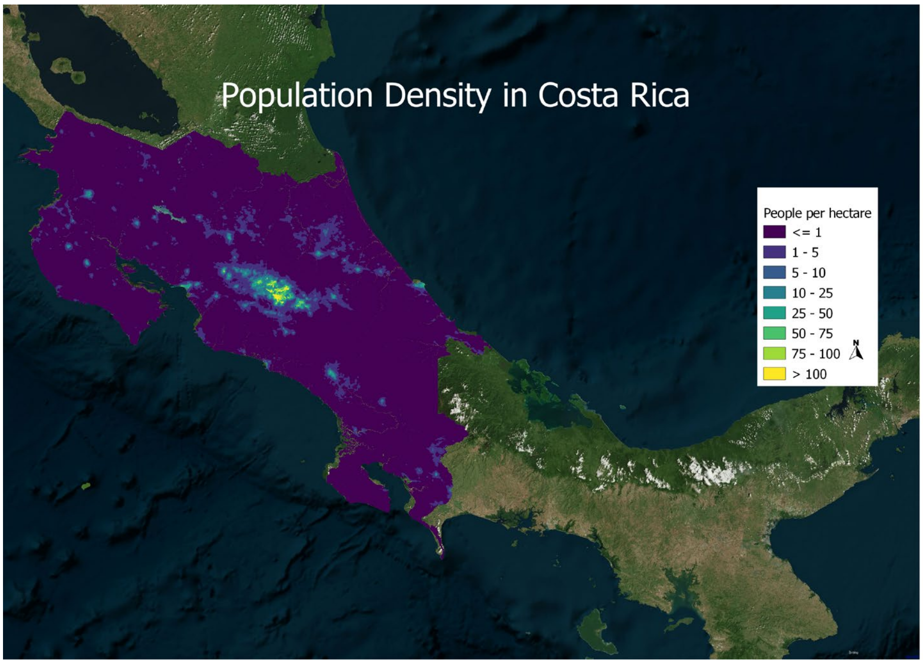
The regional breakdown used for the energy model is shown in Figure 10, and the distribution of Cost Rica's population is shown in Figure 11. The most densely populated regions in Costa Rica are in San José, in the centre and the coastal region around Limon on the Caribbean Sea. In the mountain ranges and the regions towards the borders with Nicaragua in the north and with Panama in the south, the population density is significantly lower.

Figure 10: Regional breakdown of Costa Rica for the power sector analysis



Source: ISF mapping, September 2019

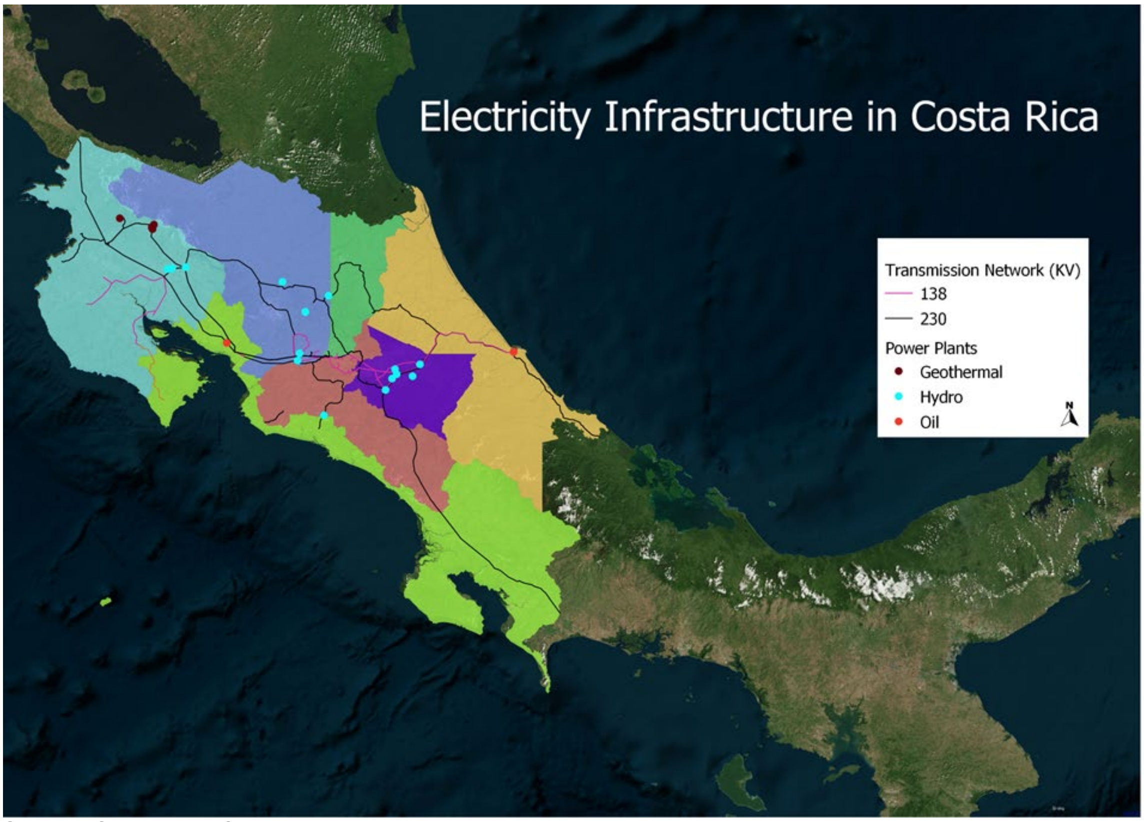
Figure 11: Distribution of population in Costa Rica



Source: ISF mapping, September 2019

Figure 12 combines the population distribution and existing electricity infrastructure (power lines and power plants over 50 MW) with the different types of grids and power stations in the country. The different coloured dots mark grid-connected power plants—each colour represents one technology, identified in the legend. The population density increases from light yellow (low population density) to red (high population density). The lines represent power transmission power lines with different voltage levels. No GIS-based data on existing solar photovoltaic or onshore wind power plants are available.

Figure 12: Existing electricity infrastructure by type



Source: ISF mapping, September 2019

2.8 RENEWABLE ENERGY POTENTIAL

Costa Rica has a largely untapped potential for renewable energy, and the only resource used significantly is biomass. Biomass and geothermal resources are both utilized in the heating and power sectors. Hydro power has only minor potential for further increase because Costa Rica's utilization rate for hydro power plants is already close to the maximum level in terms of sustainability. Solar energy is abundant, with excellent potential for utility-scale photovoltaic power stations. However, solar photovoltaic is surprisingly underutilized compared with the available solar resource and the low generation costs. This is attributable to unfavourable policies in regard to grid connection, feed-in rates, and construction permits.

Costa Rica's wind resources are concentrated in the north-western region of Guanacaste, which extends between Lake Managua and the Pacific Coast.

2.8.1 SOLAR POTENTIAL ANALYSIS BY UTS-ISF

The average annual solar radiation levels in Costa Rica are 3.2–4.8 kWh/m^2 per day (SolarGIS 2019)[47]. Because of its tropical climate and therefore high cloud coverage, Cost Rica is unsuitable for concentrated solar power. According to the International Renewable Energy Agency, Costa Rica had an installed solar capacity of 28 MW, including rooftop photovoltaics, at the end of December 2018 (IRENA 2019)[48].

Costa Rica's solar potential has been mapped under three different scenarios.

1. Available land—restricted by nature conservation, agricultural, commercial, or urban use (LU)

2. See above, with two additional restrictions: (1): maximum 10 km from existing transmission lines (PT); and (2) contiguous areas (CA)—fractured areas of less than 1 km^2 are excluded.

3. See above, with an additional restriction: (3) slope of less than 30% (mountain areas) and additional land-use restrictions.

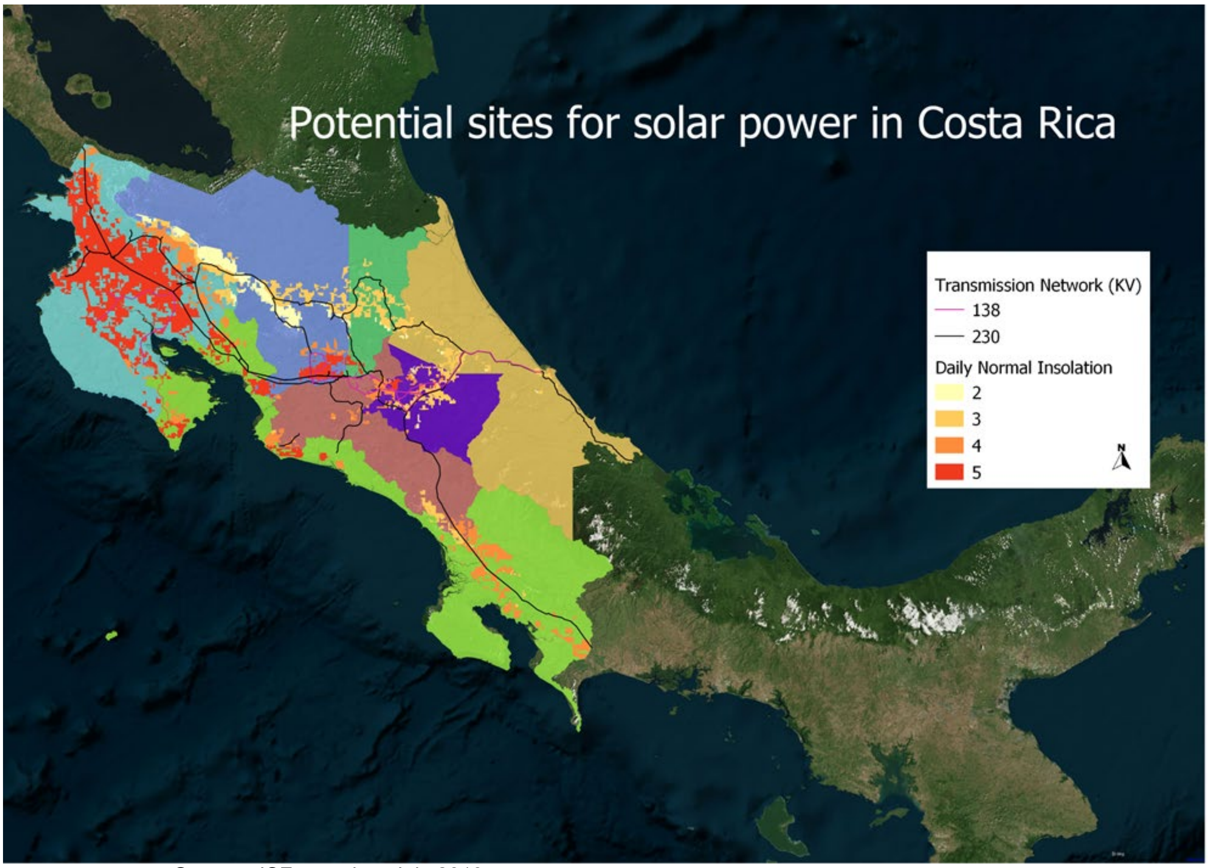
Table 20: Utility-scale solar potential for Costa Rica under different restrictions

Solar potential restrictions	Solar area in km^2	Solar potential in GW
LU	12,719.42	317.9
LU + PT + CA	12,606.49	315.1
LU + PT + CA + S30	8,126.01	203.1

Figure 13 shows the land available for utility-scale solar photovoltaics under the LU restrictions, but without further restrictions, such as proximity to transmission lines or slope. When restricted by its proximity to power lines and terrain slope the solar potential decreases. Under this scenario, Costa Rica has over 8,000 km^2 of land on which 200 GW of solar power can potentially be harvested by utility-scale solar farms. To avoid conflicts with national parks and other competing uses of land, only perennial cropland and open bushland land-cover types were included in the analysis. Only utility-scale solar energy has been included in the analysis. The (additional) roof-top potential has not been calculated.

[47] SolarGIS – online database, viewed November 2019; https://solargis.com/maps-and-gis-data/download/costa-rica
[48] IRENA (2019) – Renewable Capacity Statistics 2019, https://www.irena.org/publications/2019/Mar/Renewable-Capacity-Statistics-2019

Figure 13: Potential for utility-scale solar energy generation in Costa Rica



Source: ISF mapping, July 2019

2.8.2 Wind potential analysis by UTS-ISF

Wind Energy

Currently, Costa Rica's total installed wind power capacity is about 408 MW of onshore wind farms[48]. All projects are concentrated in Guanacaste, in the north-west of the country. There are currently no offshore wind farms on the Pacific or Atlantic coast of Costa Rica.

Onshore Wind

The overall wind resources on land are concentrated in the north west of Costa Rica with the average annual wind speeds in the range of 6 to 7 m/s.
Costa Rica's wind potential has been mapped under four different scenarios.

1. Available land——restricted by nature conservation, agricultural, commercial, or urban use (LU).
2. See above, with additional restriction: (1): maximum 10 km from transmission lines (PT).
3. See above, with additional restriction: (2) contiguous areas (CA).
4. See above, with additional restriction: (3) slope less than 30% (mountain areas) and additional land use restriction (S30).

Table 21 shows that the onshore wind potential for utility-scale wind farms under the assumed land-use restrictions is as high as 22.8 GW (see Figure 9). If mountain areas with slopes of > 30%, fractured spaces less than 1 km^2, and areas at more than 10 km from a power line are excluded, this potential reduces to 15 GW.

Onshore wind potential restrictions	Onshore wind area in km^2	Onshore wind potential in GW
LU + WS	5,699.34	22.8
LU + WS + CA	4,550.40	18.2
LU + WS + PT + CA + S30	3,749.49	15.0

Table 21: Onshore wind potential for Cost Rica under different restrictions

Offshore Wind

Costa Rica has some offshore wind potential, with average wind speeds up to 8–10 m/s, leading to capacity factors of around 3000 h per year. In this analysis, we did not use offshore wind for renewable power generation because the resource is significantly lower than required to operate economically with currently available installation costs. Furthermore, the best offshore wind conditions are off the coast of Guanacaste, where the country's best onshore wind resources are located. The low population density in this region and the lack of high-voltage power lines would lead to additional costs for transmission. Therefore, offshore wind would directly compete with the currently more economic onshore wind power generation in Costa Rica. Protected marine areas should ne be use for offshore wind farms. The overall potential for wind power in Costa Rica is significantly higher than current demand. Therefore, there is no need to utilize protected areas for wind farms.

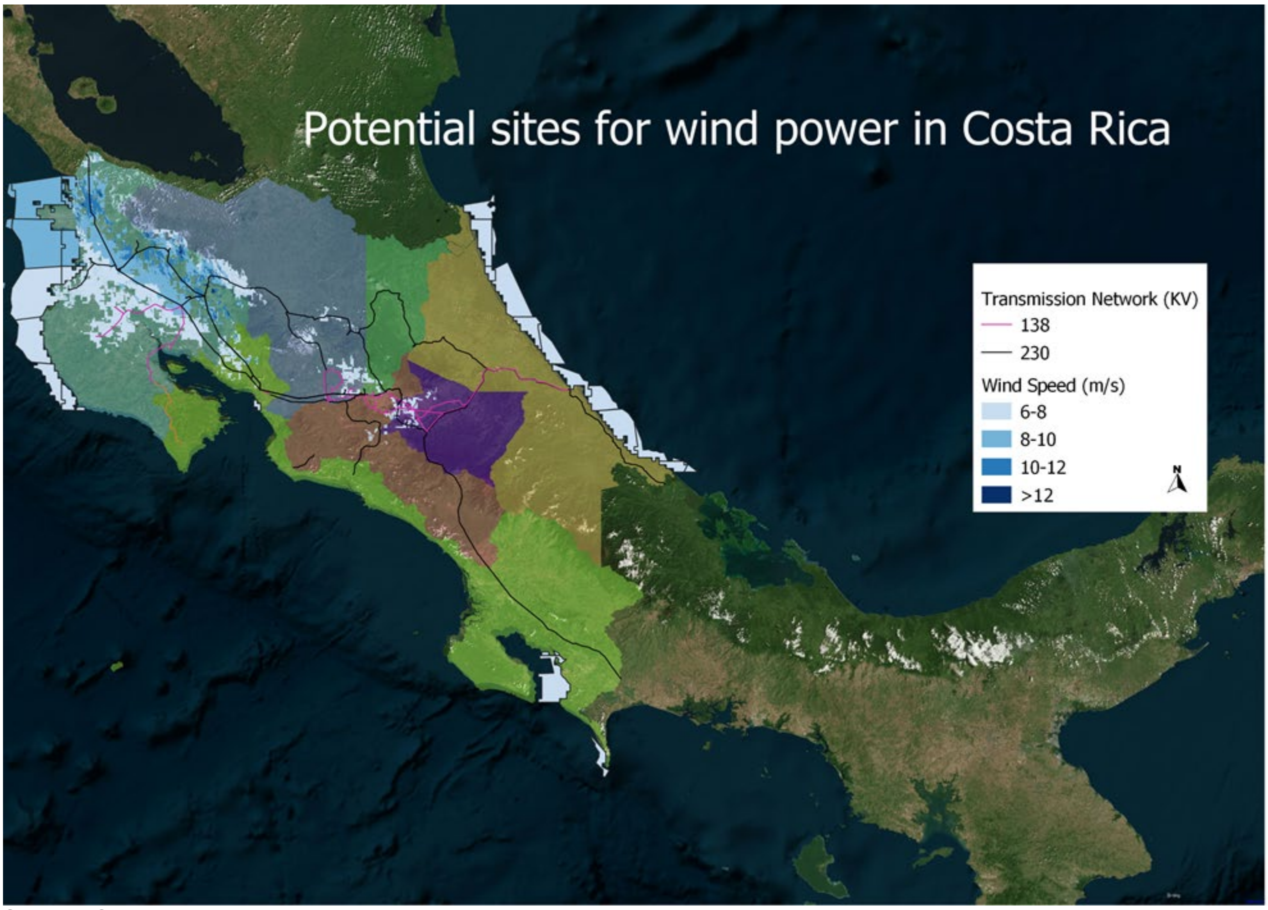
This analysis considers coastal areas with a maximum water depth of 50 m and a maximum distance to shore of 70 km. Within these restrictions, Cost Rica has a technical potential of 27 GW, spread over 6,800 km^2.

Further research is required to locate the exact offshore wind areas, both in terms of their distance to shipping lines, fisheries, and marine protection areas, their access to infrastructure, such as the power grid, and their access to harbour facilities for the operation and maintenance of wind farms. The offshore gas sector can benefit from the increased deployment of offshore wind power because workers and parts of the infrastructure can be re-used (e.g., ships, supply equipment).

Table 22: Offshore wind potential for Costa Rica under different restrictions

Offshore wind potential restrictions	Offshore wind area in km^2	Offshore wind potential in GW
Offshore 50 m / 70 km (incl. 5 m/s)	6,835.93	27.3
Offshore 50 m / 70 km (excl. 5 m/s)	2,850.22	11.4
Offshore 100 m / 70 km (incl. 5 m/s)	13,597.47	54.4
Offshore 100 m / 70 km (excl. 5 m/s)	5,188.93	20.8

Figure 14: On- and offshore wind energy generation potential in Costa Rica



Source: ISF mapping, July 2019

2.8.3 OVERVIEW OF SOLAR AND WIND POTENTIAL FOR COSTA RICA BY REGION

Table 22 shows Costa Rica's potential for utility-scale solar and wind power generation under the most restricted scenarios described in section 2.8

Table 23: Overview—Costa Rica's utility-scale solar photovoltaic, onshore wind, and offshore wind potential within 10 km of existing power lines

Cluster	Solar Area in km^2	Solar Potential in GW	Onshore Wind Area in km^2	Onshore Wind Potential in GW
Alajuela	1,584.01	39.60	472.81	1.89
Cartago	483.89	12.10	89.62	0.36
Guanacaste	3,734.38	93.36	3,101.44	12.41
Heredia	381.13	9.53	29.81	0.12
Limon	271.59	6.79	-	-
Puntarenas	1,112.53	27.81	80.92	0.32
San Jose	283.15	7.08	19.42	0.08
Total	7,850.68	196.27	3,794.03	15.18

2.9 ECONOMIC AND POLICY ASSUMPTIONS

In February 2019, the Government of Costa Rica launched its *Decarbonization Plan*, which defines activities in key sectors to be implemented in three steps until 2050 in order to achieve a modern, emission-free, resilient, and inclusive economy.[49] The Plan underpins the National Plan for Development and Public Investments and the long-term Plan Estratégico Costa Rica 2050. To reach this goal, Costa Rica will make changes and modifications to mobility and transport (both public and private), optimize energy management, promote sustainable construction and industry, and improve recycling and waste disposal. The Plan offers a roadmap to promote the modernization of Costa Rica's economy, generate jobs, and boost its growth based on the generation of "3D" services and goods: Decarbonized, Digitized, and Decentralized. The planned measures, activities, and improvements also form part of the country's extended Nationally Determined Contributions (NDCs), which Costa Rica will present to the UNFCCC in 2020. This will demonstrate and strengthen its commitment to reducing greenhouse gas emissions and its participation in the global effort to avoid a temperature rise above 2 °C relative to the pre-industrial era.

The REFERENCE scenario in this analysis is consistent with the *Plan de Expansion de La Generation Electrica* from May 2019 and suggests two additional scenarios, which go further in regard to the deployment of renewable energy and energy efficiency across all sectors.

With the reductions in the prices of solar photovoltaic and onshore wind energy that have occurred in recent years, renewables have become an economic alternative to building new gas power plants. Consequently, renewables have achieved a global market share of over 60% of all newly built power plants since 2014. Costa Rica has significant solar and wind resources and some additional potential for offshore wind.

The costs of renewable power generation are generally lower in situations with greater solar radiation and higher wind speeds. However, constantly shifting policy frameworks often lead to high investment risks, and therefore to higher project development and installation costs for solar and wind projects relative to those in countries with more stable policies.

The scenario-building processes for all scenarios include assumptions about policy stability, the role of future energy utilities, centralized fossil-fuel-based power generation, population and GDP, firm capacity, and future costs.

- **Policy stability:** This research assumes that Costa Rica will establish a secure and stable framework for the deployment of renewable power generation. In essence, financing a gas power plant or a wind farm is quite similar. In both cases, a power purchase agreement, which ensures a relatively stable price for a specific quantity of electricity, is required to finance the project. Daily spot market prices for electricity and/or renewable energy or carbon are insufficient for long-term investment decisions for any kind of power plant with a technical lifetime of 20 years or longer. In short, the better the investment certainty, the lower the cost of capital.
- **Strengthened energy efficiency policies:** Existing policy settings (i.e., the energy efficiency standards for electrical applications, buildings, and vehicles) must be strengthened to maximize the cost-efficient use of renewable energy and achieve high energy productivity by 2030.
- **Role of future energy utilities:** With the 'grid parity' of rooftop solar photovoltaics under most current retail tariffs, this modelling assumes that energy utilities of the future will take up the challenge of increased local generation and develop new business models that focus on energy services, rather than simply on selling kilowatt-hours.
- **Population and GDP:** All three scenarios are based on the same population and GDP assumptions. The projections of population growth are documented in Table 11 in section 2.4.
- **Cost assumptions:** The same cost assumptions are used across all three scenarios. Because technology costs decline as the scale of deployment increases rather than with time, the renewable energy cost reduction potential in both RENEWABLES scenarios may be even larger than in the REFERENCE scenario because of the larger market sizes. The reverse is true for the fuel cost assumptions because all the scenarios are based on the same fossil fuel price projections. However, whereas both RENEWABLES scenarios have a significant drop in demand, the REFERENCE scenario assumes an increased demand, which may lead to higher fuel costs. Therefore, these costs should be considered conservative. The cost assumptions are documented in section 5.3.

[49] https://presidencia.go.cr/wp-content/uploads/2019/05/National-Decarbonization-Plan-Costa-Rica.pdf

2.10 ASSUMPTIONS FOR SCENARIOS

2.10.1 REFERENCE SCENARIO

Costa Rica's *Plan de Expansión de La Generación Eléctrica* (GEP 2019)[6], which was published in May 2019, was taken as the basis for the REFERENCE scenario. The cost of new power plants, fuel costs, and GDP and population developments were co-ordinated with the Universidad de Costa Rica (UCR) in San José[50], which worked on an energy analysis for Costa Rica at the same time. The objective of the REFERENCE scenario is to provide a complete power supply with renewable energy, but not a complete decarbonization of the industry and transport sector.

2.10.2 ASSUMPTIONS FOR BOTH RENEWABLES SCENARIOS

Both the RE1 and RE2 scenarios are built on a framework of targets and assumptions that strongly influence the development of the individual technological and structural pathways for each sector. The main assumptions made in this scenario-building process are detailed below.

- **Emissions reductions:** The main measures undertaken to reduce CO_2 emission in the RE1 and RE2 scenarios include strong improvements in energy efficiency, resulting in an increase in energy productivity of 30% between 2020 and 2030, and the dynamic expansion of renewable energy across all sectors.
- **Renewables industry growth:** The dynamic growth of new capacities for renewable heat and power generation is assumed, based on current knowledge of potentials, costs, and recent trends in renewable energy deployment (see energy potentials, discussed in section 2.8). Communities will play a significant role in the expansion of renewables, particularly in terms of project development, the inclusion of local populations, and the operation of regional and/or community-owned renewable power projects.
- **Future power supply:** The capacity of large hydro power and bio-energy facilities will grow slowly and within economic and ecological limits. The supply from all bio-energy facilities supported by sustainable biofuels is a key issue and may come from either within Costa Rica or from certified imports. Wind power (onshore) and solar photovoltaic power are expected to be the main pillars of the future power supply, complemented by contributions from bio-energy and geothermal power plants. Hydro power is expected to remain an important pillar of Costa Rica's power supply. The solar photovoltaic figures combine both rooftop and utility-scale photovoltaic plants. The potential for offshore wind is significantly lower than that for onshore wind, so wind power generation under both RENEWABLES scenarios will concentrate on onshore wind. The solar resources for concentrated solar power are insufficient and are therefore not included in the analysis.
- **Firm capacity:** The scale of each technology deployed and the combination of technologies in each of the scenarios are designed to target a firm capacity. Firm capacity is the "proportion of the maximum possible power that can reliably contribute towards meeting the peak power demand when needed."[51] The firm capacity is important to ensure a reliable and secure energy system. Note that variable renewables also have a firm capacity rating, and the combination of technology options increases the firm capacity of a portfolio of options. Storage will add to the firm capacity as the share of variable power generation increases.
- **Security of energy supply:** The scenarios limit the share of variable power generation and maintain a sufficient share of controllable, secured capacity. This includes storage technologies. Power generation from biomass or hydro power, and a share of gas-fired back-up capacity and storage, are considered important for the security of supply in a future energy system, and are related to the output of the firm capacity discussed above.
- **Sustainable biomass levels:** The sustainable level of biomass used in Costa Rica is assumed to be in the range of 580 MW[52] (also see GEP 2019, page 52). However another assessment found a significant higher bio-energy potential of 2530 MW (Huttunen 2005)[53].
- **Electrification of transport**: Efficiency savings in the transport sector will result from fleet penetration by new highly efficient vehicles, such as electric vehicles, but also from assumed changes in mobility patterns and the implementation of efficiency measures for combustion engines. The RE scenarios assume a limited use of biofuels for transportation, given the limited supply of sustainable biofuels.
- **Hydrogen and synthetic fuels:** Hydrogen and synthetic fuels, generated by electrolysis using renewable electricity, can be introduced as a third renewable fuel in the transportation sector,

[50] Universidad de Costa Rica, EPERLab and the leadership of Jairo Quiros-Tortos
[51] http://igrid.net.au/resources/downloads/project4/D-CODE_User_Manual.pdf
[52] Acciones de Mitigación Nacionalmente Apropiadas Energía Biomasa NAMA, MINAE, Dirección Cambio Climático (DCC), MAG, ICE, MIDEPLAN. 2016
[53] Huttunen (2005), RESEARCH REPORTS IN BIOLOGICAL AND ENVIRONMENTAL SCIENCES, Suvi Huttunen and Ari Lampinen, BIOENERGY TECHNOLOGY EVALUATION ANDPOTENTIAL IN COSTA RICA, UNIVERSITY OF JYVÄSKYLÄ, 2005

complementing biofuels, the direct use of renewable electricity, and battery storage. Hydrogen generation can have high energy losses. However, the limited potential of biofuels and probably also of battery storage for electric mobility means it will be necessary to have a third renewable option in the transport sector. Alternatively, renewable hydrogen could be converted into synthetic methane and liquid fuels, depending on the economic benefits (storage costs versus additional losses) and the technological and market developments in the transport sector (combustion engines versus fuel cells). Hydrogen and synthetic fuels will be imported. In the industry sector, hydrogen can be an additional renewable fuel option for high-temperature applications, supplementing biomass in industrial processes whenever the direct use of renewable electricity is not possible. In this analysis, we did not include hydrogen or synthetic fuels, but recommend their use as a replacement for natural gas after 2035 when a 100% renewable energy scenario is desired.

2.10.2.1 Assumptions for RENEWABLES 1

The RENEWABLES 1 scenario (RE1) is designed to meet Costa Rica's energy-related targets and to lead towards a pathway of 100% renewable energy by 2050. Diesel power plants will be phased-out by 2025 and replaced by renewables. Both the heating and the transport sectors will start to replace fossil fuels with electricity where it is economically possible. Thermal renewables for heating, mainly solar- and bio-energy-based generation, will replace fossil fuels.

Energy efficiency and renewable energy generation technologies will have moderate implementation growth rates during the first decade until 2030. Electric mobility will grow steadily over the entire modelling period (until 2050) and replace combustion engines entirely by 2050. The RENEWABLES 1 scenario aims to remain at today's energy-related CO_2 emission level, despite economic and population growth, for the entire energy sector and decarbonize the power sector between 2020 and 2025.

2.10.2.2 Assumptions for RENEWABLES 2

The RENEWABLES 2 scenario (RE2) is more ambitious than the RENEWABLES 1 scenario, but follows the same technology pathways. The decarbonization of the transport sector will be achieved by 2050, leading to a higher electricity demand than in the RE1 scenario. Energy efficiency will play an accelerating role and leads to a lower final energy demand (15% less than RE1). RENEWABLES 2 has a target to decarbonize Costa Rica's energy sector entirely by 2050.

3 KEY RESULTS FOR COSTA RICA: LONG-TERM ENERGY SCENARIO

In this section, we outline the key results across a range of areas, both in terms of the impacts and the costs of the different scenarios. First, we consider stationary energy, focusing on electricity generation, capacity, and breakdown by technology. We then examine the energy supply for heating, focusing on the industrial heat supply. This is followed by a consideration of the impacts and costs of the different scenarios on transport and the development of CO_2 emissions. The chapter ends with an examination of the final costs, and an outline of the required energy budget.

This chapter provides an overview of three energy pathways for Costa Rica until 2050, focusing on the 2030 results. The scenarios describe a holistic approach to the entire energy sector—power, heat, process heat, and transport. Increased electrical mobility and the electrification of heating processes will lead to "*sector coupling*" or the interconnection of historically rather separate energy sectors. As a result, the electricity demand will increase, even under ambitious electricity efficiency assumptions. Therefore, the following chapter, Chapter 4—power sector analysis—focuses entirely on the electricity sector.

3.1 COSTA RICA: FINAL ENERGY DEMAND

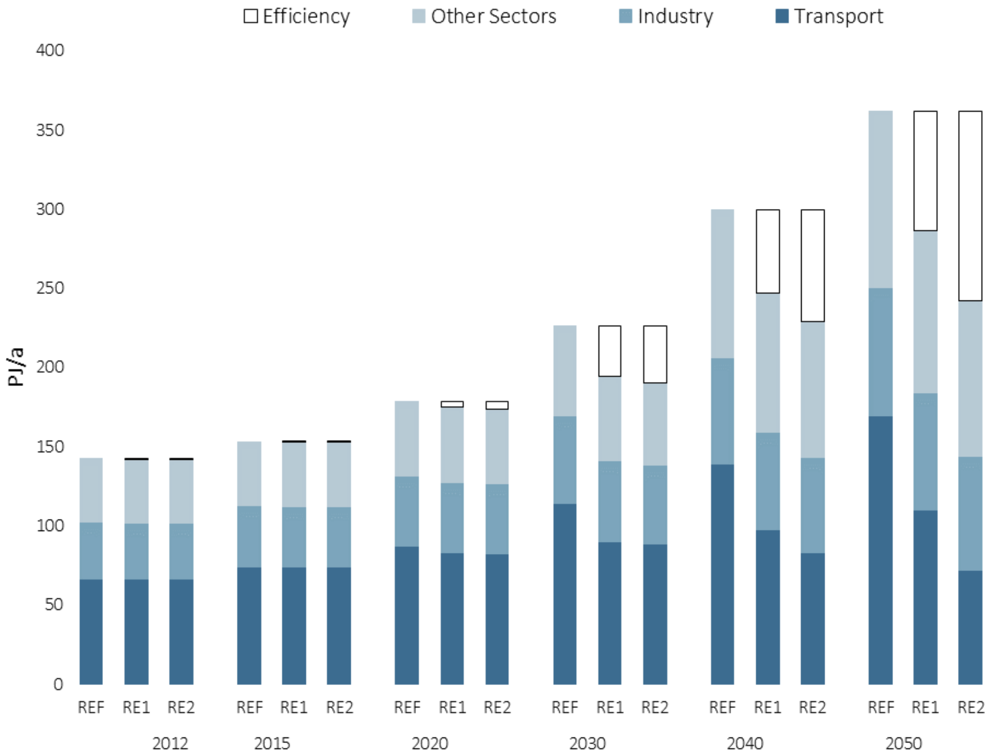
We combined the projections for population development, GDP growth, and energy intensity to generate the future development pathways for Costa Rica's final energy demand. This includes the electricity demand development, which was calculated with a bottom-up analysis. The final energy demands are shown in Figure 15 for the REFERENCE and RENEWABLES scenarios. Under the REFERENCE scenario, the total final energy demand will increases by 150%, from 150 PJ/a in the base year to 360 PJ/a in 2050. In the RE1 scenario, the final energy demand will increase at a much lower rate (by 93%) compared with current consumption, and is expected to reach 290 PJ/a by 2050. The RE2 scenario will result in some additional reductions—to 244 PJ/a—which are the result of a higher proportion of electric cars (see section 3.4).

Under both alternative scenarios, the overall electricity demand is expected to increase in response to economic growth, higher living standards, and the electrification of the transport sector, despite efficiency gains in all sectors (see Figure 15) The total electricity demand will increase from about 10 TWh/a in the base year to 30 TWh/a by 2050 in the RE1 scenario. Compared with the REF scenario, efficiency measures in the industry, residential, and service sectors will avoid the generation of about 0.8 TWh/a.

This reduction can be achieved, in particular, by introducing highly efficient electronic devices, using the best available technology, in all demand sectors. It is assumed that the implementation of efficient devices across all sectors will mainly occur in response to strict and ever-evolving efficiency standards. The Japanese "top-runner" model was particularly successful because it included competitive incentives for the private sector and avoided additional subsidies. The advanced RE2 scenario includes more ambitious electrification, particularly of the transport sector, but implements stricter efficiency standards. As result, the electricity demand will increase to 26 TWh/a by 2040 and further to 43 TWh by 2050. Electricity will become the major renewable 'primary' energy, not only for direct use for various purposes, but also for the generation of synthetic fuels to substitute for fossil fuels. Around 20 TWh will be used in 2050 for electric vehicles and rail transport (excluding bunkers) under the RE2 scenario.

Efficiency gains in the heating sector will be even larger than those in the electricity sector. Under the RE2 scenario, energy consumption equivalent to about 6 PJ/a will be avoided as a result of efficiency gains by 2030 compared with the REF scenario. This reduction is mainly attributable to increased efficiency measures in process heat for industry. The development of the energy intensity for the industry sector is assumed to decrease faster in both alternative scenarios than in the REF scenario.

Figure 15: Costa Rica—Projection of total final energy demand by sector (Excluding non-energy use and heat from CHP auto-producers)



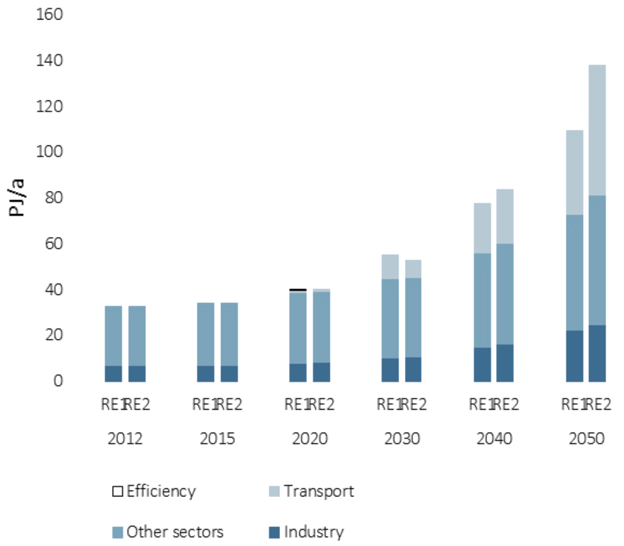


Figure 16: Costa Rica—Development of the electricity demand by sector in both RENEWABLES scenarios

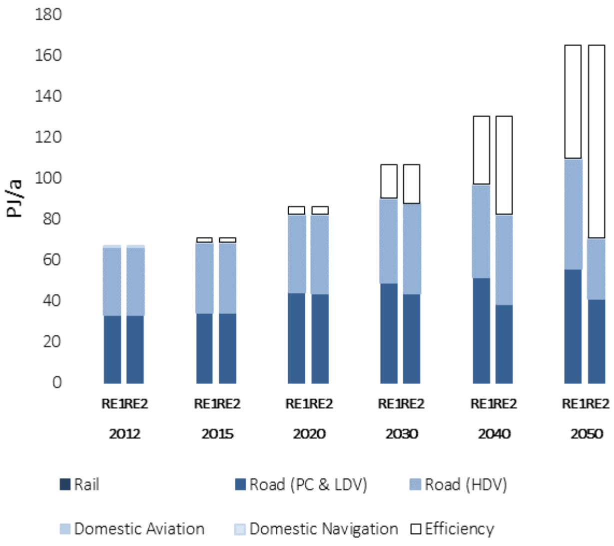


Figure 17: Costa Rica—Development of the final energy demand for transport by sector in both RENEWABLES scenarios

3.2 ELECTRICITY GENERATION

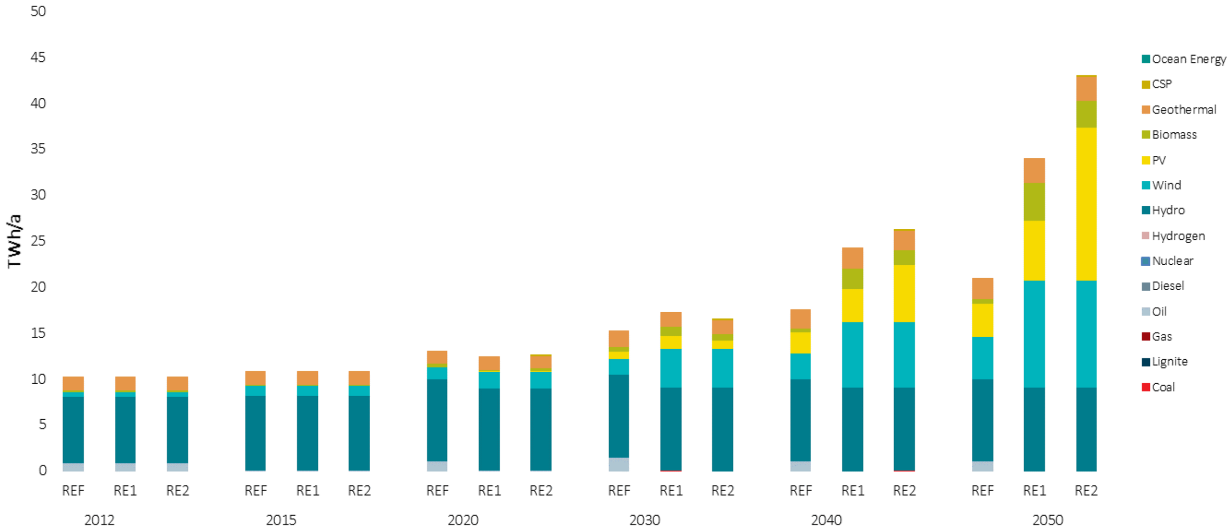
The development of the electricity supply sector will be characterized by a dynamically growing renewable energy market and an increasing share of renewable electricity. This trend will more than compensate the phase-out of oil power plants by 2025 and the increased electricity demand due to electric mobility under both alternative scenarios. By 2030, 100% of the electricity produced in Costa Rica will come from renewable energy sources in all three scenarios. In the RE1 'new' renewables—mainly solar photovoltaic and onshore wind - will contribute 33% to the total electricity generation in 2030 and 54% by 2050. The installed capacity of renewables will reach close to 5,500 MW in 2030 and 12,800 MW by 2050.

Table 24: Costa Rica—Projections of renewable electricity generation capacity

In MW		2015	2020	2030	2040	2050
Hydro	REF	1,935	2,356	2,375	2,375	2,375
	RE1	1,935	2,342	2,401	2,401	2,401
	RE2	1,935	2,342	2,401	2,401	2,401
Biomass	REF	40	82	85	86	104
	RE1	40	43	167	403	793
	RE2	40	48	120	285	555
Wind	REF	396	408	490	810	1,318
	RE1	396	737	1,552	2,527	4,115
	RE2	396	737	1,552	2,527	4,116
Geothermal	REF	208	262	322	375	415
	RE1	208	262	322	336	385
	RE2	208	262	322	336	385
PV	REF	3	28	585	1,517	2,472
	RE1	3	35	1,093	2,770	5,080
	RE2	3	56	741	4,762	12,857
Total	REF	2,682	3,123	3,858	5,165	6,684
	RE1	2,681	3,347	5,437	8,417	12,774
	RE2	2,681	3,384	5,038	10,290	20,313

The RE2 scenario will also achieve 100% renewable electricity generation in 2030. However, the renewable capacity will increase after 2030 beyond the RE1 values due to more ambitious electric mobility. The capacity will reach 10,300 MW by 2040 and 20,300 MW in 2050, around 8,000 MW higher than under the RE1 scenario. Table 24 shows the comparative evolution of the different renewable technologies in Costa Rica over time. The installed capacity of hydro power will dominate, as a major renewable power capacity, for decades but will be overtaken by solar photovoltaics in 2040, which will remain the largest renewable power capacity throughout the remaining scenario period. Wind power will increase in both RENEWABLES scenarios to just over 4,000 MW, whereas hydro power will remain around 2,400 MW as well. Both RENEWABLES scenarios will result in a high proportion of variable power generation sources (photovoltaics and wind): 33%–31% by 2030 and 54%–66% by 2050. Therefore, smart grids, demand-side management, energy storage capacities, and other options must be expanded to increase the flexibility of the power system to ensure grid integration, load balancing, and a secure supply of electricity.

Figure 18: Costa Rica—Breakdown of electricity generation by technology



The calculated potential for utility-scale solar power plants (PV) under all restrictions and excluding areas further than 10 km from transmission lines is 203,000 MW. Even the most ambitious RE2 scenario can be implemented with the utilisation of only 6% of the utility-scale solar power plant potential. Additional to this potential, Costa Rica has a significant rooftop solar photovoltaic potential. The RE1 scenario has less solar photovoltaic power generation and wind power generation because of lower electrification rates in the industry and transport sector.

In terms of onshore wind, both alternative scenarios use around 25% of the onshore wind potential, with the greatest restriction identified in section 2.8.2, until 2050. However, the wind resource is concentrated in only one region, Guanacaste, so the transmission capacity must be increased to distribute the electricity across the country (see section 4).

3.3 ENERGY SUPPLY FOR COOKING AND INDUSTRIAL PROCESS HEAT

Today, renewables meet around 60% of Costa Rica's energy demand for heating, with the main contribution from biomass. Dedicated support instruments are required to ensure the dynamic development of renewables, particularly for renewable technologies and renewable process heat production in the industry sector. In the RE1 scenario, renewables will already provide 91% of Costa Rica's total heat demand in 2030, 99% in 2040, and 100% in 2050.

- Energy efficiency measures will help to reduce the currently growing energy demand for heating by 11% in 2030 (relative to the REF scenario), despite the increased industry energy demand arising from economic growth.
- In the industry sector, solar collectors, geothermal energy (mainly heat pumps), and electricity will increasingly substitute for fossil-fuel-fired systems.
- A shift from coal and oil to natural gas in the remaining conventional applications will lead to a further reduction in CO_2 emissions.

Figure 19: Costa Rica—Projection of heat supply by energy carrier (REF, RE1, and RE2)

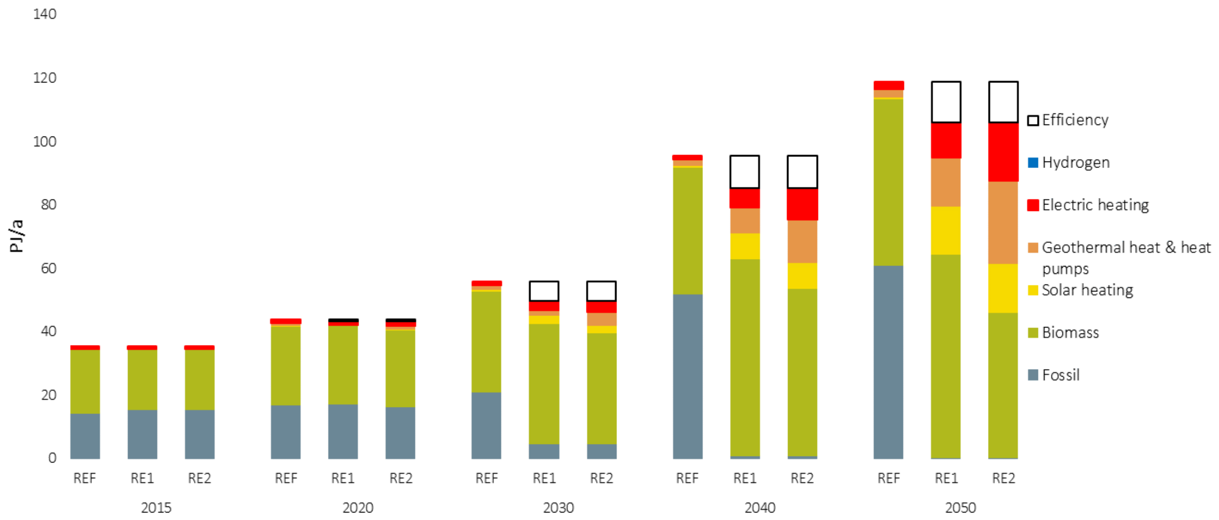


Table 25: Costa Rica—Projection of renewable heat supply

in PJ/a		2015	2020	2030	2040	2050
Biomass	REF	20	25	32	40	53
	RE 1	19	25	38	62	64
	RE 2	19	24	35	53	46
Solar heating	REF	0	0	1	1	1
	RE 1	0	0	2	8	15
	RE 2	0	0	2	8	15
Geothermal heat & heat pumps	REF	0	1	1	2	3
	RE 1	0	1	2	8	15
	RE 2	0	1	4	13	26
Hydrogen	REF	0	0	0	0	0
	RE 1	0	0	0	0	0
	RE 2	0	0	0	0	0
Total	REF	20	26	34	43	56
	RE 1	19	25	42	79	95
	RE 2	19	26	42	75	87

Table 25 shows the development of different renewable technologies for heating in Costa Rica over time. Biomass remains the main contributor, with increasing investment in highly efficient modern biomass technologies. After 2025, a massive growth in solar collectors and increasing proportions of geothermal and environmental heat will further reduce the dependence on fossil fuels. The RE2 scenario will result in the complete substitution of the remaining fossil fuel consumption, mainly by renewable electricity, by 2040.

Table 26: Costa Rica—Installed capacities for renewable heat generation

in MW		2020	2030	2040	2050
Biomass	REF	3,528	4,578	5,580	6,868
	RE 1	3,602	5,751	10,319	9,537
	RE 2	3,503	5,276	8,748	6,706
Geothermal	REF	46	114	138	159
	RE 1	46	135	603	990
	RE 2	46	135	603	990
Solar heating	REF	0	144	161	183
	RE 1	78	638	2,378	4,106
	RE 2	77	637	2,377	4,104
Heat pumps	REF	11	32	50	88
	RE 1	11	275	1,236	2,476
	RE 2	11	492	1,714	3,506
Total	REF	3,585	4,868	5,929	7,298
	RE 1	3,737	6,799	14,536	17,109
	RE 2	3,637	6,540	13,442	15,306

3.4 TRANSPORT

A key target in Costa Rica is to introduce incentives for people to drive smaller cars and buy new, more-efficient vehicles. It is also vital to shift transport use to efficient modes, such as public transport buses and shared vehicles, especially in the large expanding metropolitan area. The transport energy demand is projected to increase under all scenarios. However, the shift to electrification in the transport sector will take more than a decade, so the transport scenarios will show small differences until 2030.

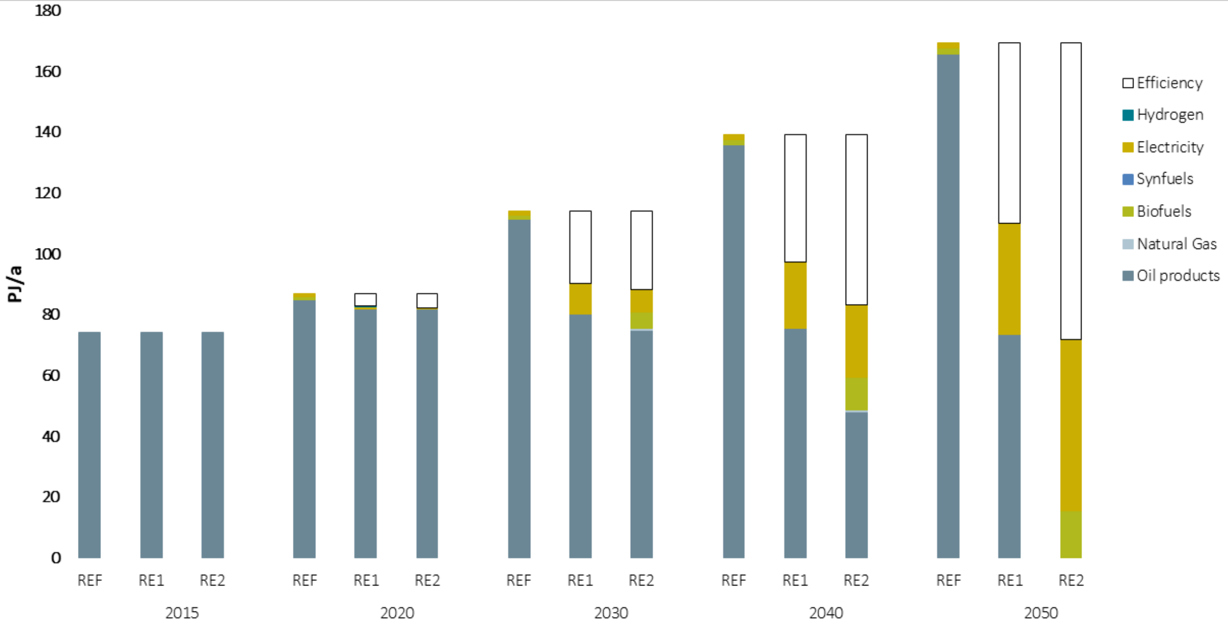
To avoid increases in—mainly oil-based—transport energy beyond 2025, the alternative scenarios implement a number of measures. It is vital to shift transport use to efficient transport modes, such as electric buses and freight vehicles, especially in the large expanding metropolitan areas. Together with rising prices for fossil fuels, these changes will slow the increase in car sales projected even under the RENEWABLES scenarios. However, the energy demand from the transport sector is expected to increase under the REF scenario at around 130 PJ/a by 2030, with a further increase thereafter to 160 PJ/a in 2050. In the RE1 scenario, efficiency measures and modal shifts will save 12% of the energy demand (13 PJ/a) by 2030 and 35% (60 PJ/a) by 2050 relative to the REF scenario.

Additional modal shifts and technology switches will lead to even higher energy savings under the RE2 scenario of 58% (100 PJ/a) in 2050 compared to the REF scenario. Highly efficient propulsion technology with hybrid, plug-in hybrid, and battery-electricity-powered trains will bring large efficiency gains. By 2030, electricity will provide 11% of the transport sector's total energy demand under the RE1 scenario, whereas in 2050, the share will be 33% (RE1) and 78% under the RE2 scenario. Hydrogen and other synthetic fuels generated with renewable electricity may be complementary power sources for the transport sector, but have not been considered in all scenarios.

Table 27: Projection of the transport energy demand by mode (excluding pipeline transport)

in PJ/a		2015	2020	2030	2040	2050
Road	REF	68.5	83.1	102.8	125.6	158.8
	RE 1	68.5	82.3	90.0	97.0	109.6
	RE 2	68.5	82.0	87.7	82.2	70.4
Domestic aviation	REF	0.1	0.1	0.1	0.2	0.2
	RE 1	0.1	0.1	0.1	0.2	0.2
	RE 2	0.1	0.1	0.1	0.2	0.2
Domestic navigation	REF	0.1	0.1	0.1	0.1	0.1
	RE 1	0.0	0.1	0.1	0.1	0.1
	RE 2	0.0	0.1	0.1	0.1	0.1
Total	REF	68.1	83.4	103.0	125.9	159.1
	RE 1	68.7	82.5	90.3	97.3	109.9
	RE 2	68.7	82.3	88.0	82.5	70.7

Figure 20: Costa Rica—Final energy consumption by transport under the scenarios

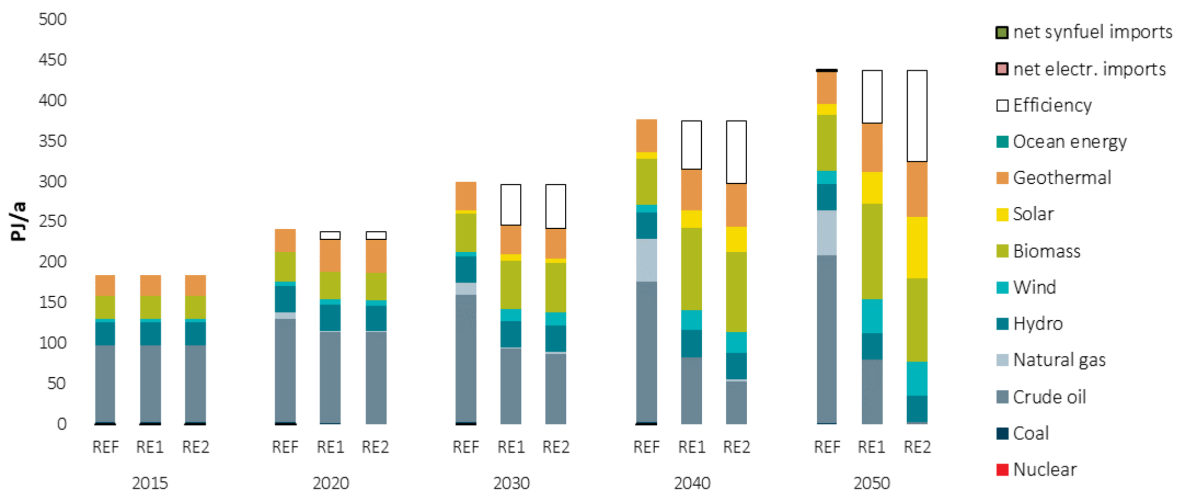


3.5 PRIMARY ENERGY CONSUMPTION

Based on the assumptions discussed above, the primary energy consumptions under both RENEWABLES scenarios and the REFERENCE scenario are shown in Figure 21. Under the RE1 scenario, the primary energy demand will increase from the present level of around 185 PJ/a to around 250 PJ/a in 2030, a reduction of 34%. Compared with the REF scenario, the overall primary energy demand will be reduced by 52 PJ by 2030 under the RE1 scenario (REF: 298 PJ in 2030). The RE2 scenario will result in a primary energy consumption of around 242 PJ in 2030. In comparison, the REF scenario will involve a consumption of 437 PJ/a by 2050, whereas the RENEWABLES scenarios will result in 372 PJ/a (RE1) and 325 PJ/a (RE2).

The RENEWABLES scenarios aim to reduce fossil fuel consumption as fast as is technically and economically possible by the expansion of renewable energy generation and the rapid introduction of very efficient vehicles to the transport sector to replace oil-based combustion engines. This will lead to an overall renewable primary energy share of 61% in 2030 and 78% in 2050 in the RE1 scenario and 100% in 2050 in the RE2 scenario (excluding non-energy consumption).

Figure 21: Costa Rica—Projection of total primary energy demand by energy carrier (incl. electricity import balance)



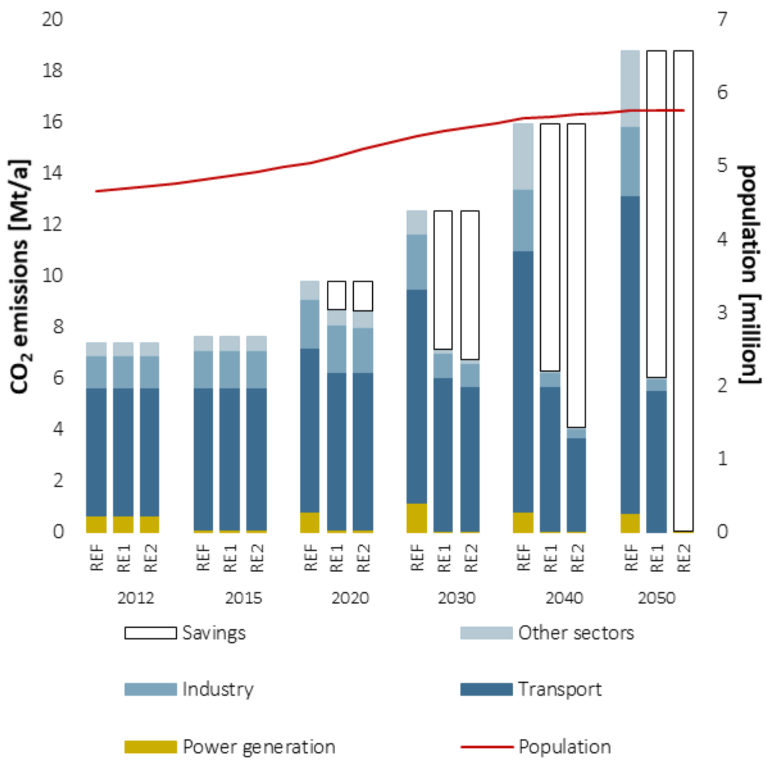
3.6 CO_2 EMISSIONS TRAJECTORIES

Costa Rica's energy-related CO_2 emissions will increase from 7.6 million tons to 12.5 million tons between 2015 and 2030 and reach 18.8 million tons CO_2 in 2050 under the REF scenario. Energy-related carbon emissions will also increase under the RE1 scenario to 7.2 million tons CO_2 by 2030, but decrease thereafter to 6 million tons CO_2 by 2050, only one third of the emissions under the REF scenario. Per capita carbon emissions will remain at around 1.5 tons CO_2 and drop to 1 ton by 2040 (RE1).

The power demand will increase by 38% in the RE1 scenario between 2020 and 2030, whereas the overall CO_2 emissions from the electricity sector will drop to one quarter of the 2020 value as a result of the oil phase-out in 2025 and increased renewable electricity deployment. Over 90% of total energy-related carbon emissions in the RE1 scenario are from the transport sector, and efficiency gains and the increased use of renewable electricity in vehicles will keep emission stable on current levels while the demand continues to increase. The transport sector will remain the largest source of emissions in 2050 under the RE1 scenario, with a 91% share of CO_2 generation.

The RE2 scenario will decarbonize the power and industry sectors by 2030, whereas the transport sector will remain responsible for 5.7 million tons of CO_2 by 2030, due to vehicles with combustion engines. Between 2020 and 2030, the RE2 scenario will reduce energy-related CO_2 emissions by 38 million tons of CO_2, whereas RE1 will save cumulative carbon emissions equivalent to 35 million tons. The greatest CO_2 emissions under the RE2 scenario will come from the transport sector, with around 15 million tons (2015-2030).

Figure 22: Costa Rica—Development of CO_2 emissions by sector under the RENEWABLES scenarios
(savings = reduction compared with the REFERENCE scenario)



3.7 COST ANALYSIS: LONG-TERM ENERGY SCENARIO

FUTURE COSTS OF ELECTRICITY GENERATION

The costs provided in this section include all the construction costs for new power plants, the average standard operation and maintenance costs for each technology, and fuel costs. The infrastructure costs for possibly required additional oil and gas storage and distribution capacities or grid expansion are not included because they are beyond the scope of this research.

Figure 23 shows the introduction of renewable technologies without carbon costs. Under the REFERENCE scenario, power generation costs will remain around US$0.06 per kWh until 2050 and decrease slightly to US$0.053 per kWh by 2050. The RE1 scenario will lead to slightly lower average generation costs of US$0.054 per kWh (2030) and US$0.051 per kWh by 2050, although this difference is within the error margin of the long-term cost projections. The most favourable results in 2050 will be under the RE2 scenario, in which the shares of solar photovoltaic and wind power are high, with lower requirements for fuel and lower capital costs for installation. However, until 2030, the costs will be identical to those under RE1. These generation costs will start to diverge by 2040, and by 2050, the RE2 scenario will achieve US$0.045 per kWh, almost US$0.01 below the REFERENCE scenario.

The level of electrification, especially in the transport sector, is the main difference between all scenarios. Thus, total generation costs are higher in the RE1 and RE2 scenarios as more electricity is generated to replace fuels—mainly oil—in the transport sector. Therefore, a cost comparison must take into account the savings in transport fuel costs.

The RE2 scenario will lead to an electricity requirement of 56.4 PJ per year (15 TWh/a) for the transport sector in 2050, to replace oil as the main transport fuel. In combination with efficiency measure, Costa Rica will save 25 million barrels of oil (155 PJ) in 2050, leading to savings of US$2.25 billion at the assumed oil price (see Table 19). In comparison, the additional electricity generation will cost around US$700 million. Therefore, the electrification of the transport in the RE2 scenario will lead to fuel cost savings of approximately US$1.5 billion.

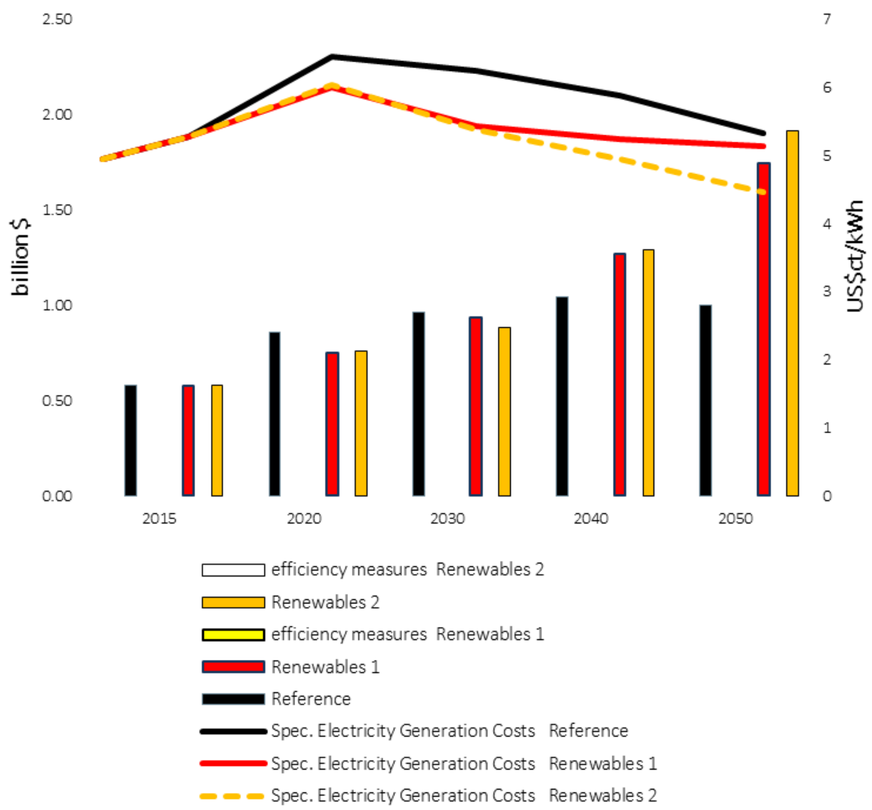
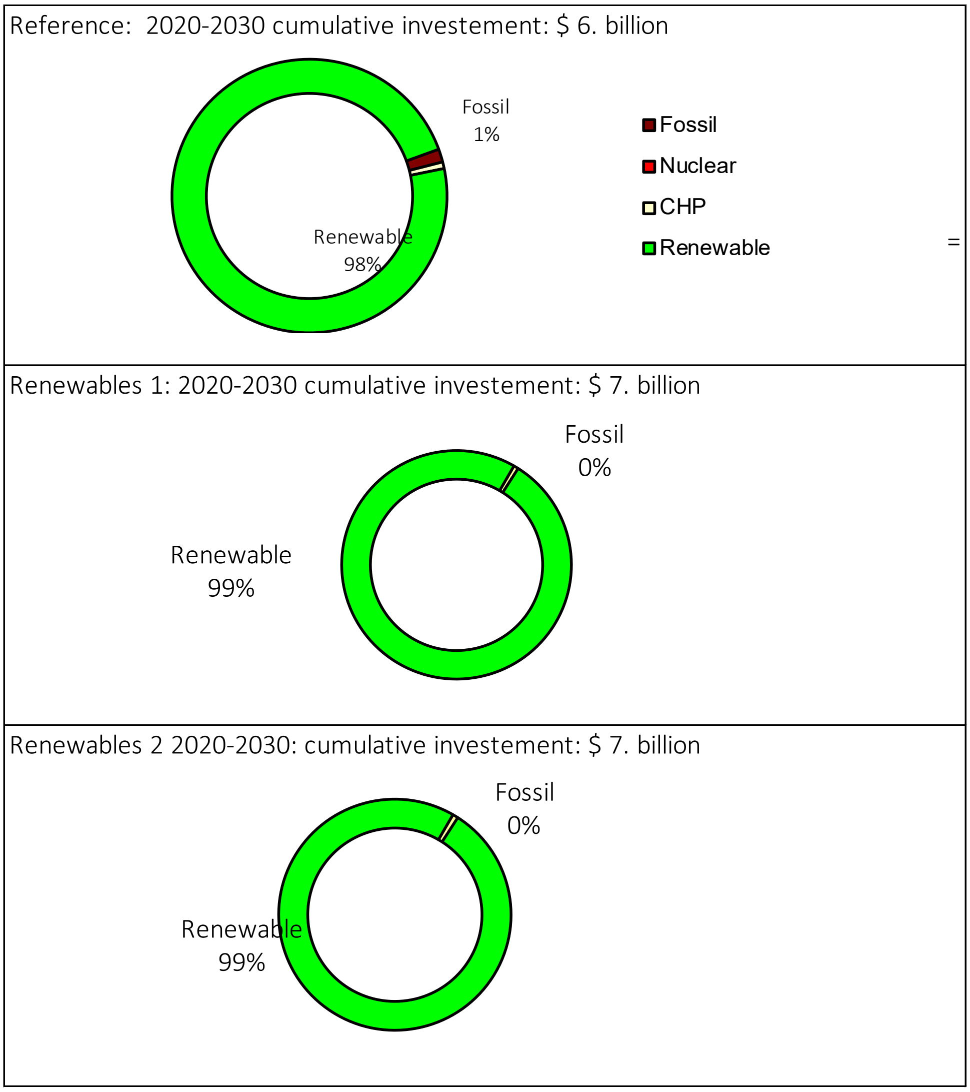


Figure 23: Costa Rica—Development of total electricity supply costs and specific electricity generation costs in the scenarios—with no carbon costs

FUTURE INVESTMENTS IN THE POWER SECTOR

Around US$7.35 billion will be required in investment between 2020 and 2030 for both RENEWABLES scenarios to become reality, US$1.8 billion more than in the REFERENCE scenario. The REFERENCE scenario will require annual investments of US$550 million, whereas both RENEABLES scenarios will lead to around US$700. The resulting additional annual investments between 2020 and 2030 will be US$150 million. Under all scenarios, investments in fossil power generation will be minor. For the whole modelling period until 2050, the RENEWABLES 1 and RENEWABLES 2 scenarios will have similar investment needs, of around US$ 30 billion over 30 years ($ 28billion / $ 31 billion). The REFERENCE scenario will require less investments—a total of US$ 19 billion over the same period, due to the lower electricity needs compared to the enhanced electrification strategy of the transport sector. The additional investments in power plants to supply the transport electricity are already reflected in the average generation costs (see previous section). In 2017, Costa Rica imported goods with a total value of $ 10.3 billion[54] - refined petroleum represent 13.7% or $1.4 billion per year – the largest single product, followed by cars (5.3% of total imports). The replacement of imported gasoline with local produced renewable electricity for transport will pay off – with current fuel prices – within 7 years.

Figure 24: Cost Rica—Cumulative investment in power generation under the three scenarios in 2020–2030



In the long term, until 2050, the fuel cost savings in the RE1 scenario will reach a total of US$5.3 billion up to 2050, or US$180 million per year. Therefore, the total fuel cost savings will cover 84% of the total additional investments compared with the REF scenario. The fuel cost savings in the power sector under the RE2 scenario will similar to those that occur under RE1, but with additional fuel costs savings in the transport sector. Renewable energy sources will then go on to produce electricity without any further fuel costs beyond 2050, whereas the costs for oil (imports) will continue to be a burden on the national economy.

[54] OECD – World, country profiles; https://oec.world/en/profile/country/cri/#Imports

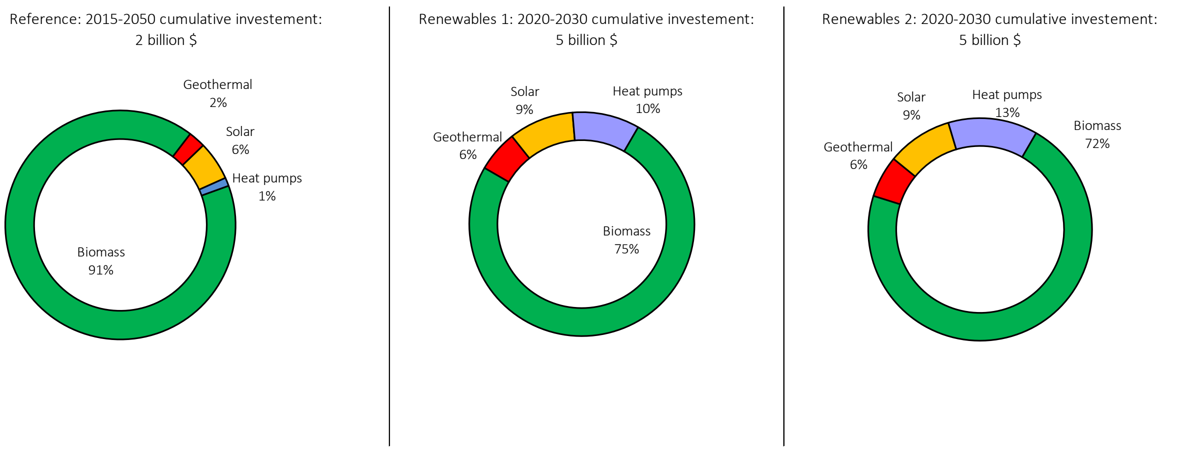
3.8 FUTURE INVESTMENTS IN THE HEATING SECTOR

Similarly, in the heating sector, both RENEWABLES scenarios will require a major revision of current investment strategies in heating technologies. In particular, solar thermal and geothermal heat pump technologies will require enormous increases in installations if their potentials are to be tapped for the—mainly industrial—heating sector. The use of biomass, especially for industrial heat demand, will also be substantial.

Renewable heating technologies are extremely variable, from unglazed solar collectors to very sophisticated enhanced geothermal and solar systems. The investment volumes in all three scenarios will be significantly different: the REF scenario will require US$2 billion, the RE1 and RE2 scenarios both US$5 billion. The large differences will result from the total system change for heat generation.

In the long term, until 2050, cost projections can only be quantitative estimates. The RENEWABLES scenarios will require around US$16.5 billion in total to be invested in renewable heating technologies up to 2050 (including investments in replacements after the economic lifetimes of the plants), or approximately US$550 million per year.

Figure 25: Costa Rica—Cumulative Investment in heat generation under the three scenarios in 2020–2030



3.9 INVESTMENT AND FUEL COST SAVINGS IN THE POWER SECTOR

Under the RE1 scenario, the additional investments between 2020 and 2030 are estimated to be US$1.8 billion, and compared with the REF scenario, the fuel cost savings will add up to US$1.5 billion, just like in the RE2 scenario. Even under the assumption that there will be large uncertainties in both future investment costs for power generation equipment and the development of fossil fuel prices, it seems certain that the overall cost balance will be economically beneficial under the RE1 scenario.

Table 28: Costa Rica—Cumulative investment costs for electricity generation and fuel cost savings under the RENEWABLES 1 scenario

CUMULATIVE INVESTMENT COSTS Difference Reference minus Renewables 1		2020-2030	2020 - 2030 average per year	2031-2040	2041-2050	2020-2050	2020 - 2050 average per year
Conventional (fossil + nuclear)	billion $	0.1	0.0	0.3	0.5	0.9	0.0
Renewables (incl. CHP)	billion $	-1.9	-0.2	-3.0	-4.7	-9.8	-0.3
Total	**billion $**	-1.8	-0.18	-2.7	-4.2	-8.7	-0.30
CUMULATIVE FUEL COST SAVINGS							
Cumulative savings Renewables 1 versus Reference							
Fuel oil	billion $	1.5	0.2	1.8	2.5	5.9	0.2
Gas	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Lignite	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear energy	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Total	**billion $**	1.5	0.15	1.8	2.5	5.9	0.18

Under the RE2 scenario, the additional investment between 2020 and 2050 is estimated to be around US$12.6 billion compared with the REF scenario. The fuel cost savings will add up to US$5.9 billion. Thus, the fuel cost savings can only re-finance the additional investment in power generation if the fuel cost savings in the transport and industrial heating sectors are considered.

Table 29: Costa Rica—Cumulative investment costs for electricity generation and fuel cost savings under the Renewables 2 scenario

CUMULATIVE INVESTMENT COSTS Difference Reference minus Renewables 1		2020-2030	2020 - 2030 average per year	2031-2040	2041-2050	2020-2050	2020 - 2050 average per year
Conventional (fossil + nuclear)	billion $	0.1	0.0	0.3	0.5	0.9	0.0
Renewables (incl. CHP)	billion $	-1.5	-0.1	-4.5	-7.4	-13.4	-0.4
Total	**billion $**	-1.4	-0.17	-4.2	-4.2	-12.6	-0.42
CUMULATIVE FUEL COST SAVINGS							
Cumulative savings Renewables 1 versus Reference							
Fuel oil	billion $	1.5	0.2	1.8	2.5	5.9	0.2
Gas	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Hard coal	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Lignite	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Nuclear energy	billion $	0.0	0.0	0.0	0.0	0.0	0.0
Total	**billion $**	1.5	0.15	1.8	2.5	5.9	0.18

4 COSTA RICA: POWER SECTOR ANALYSIS

In this chapter, we summarize the results of the hourly simulations of the long-term scenarios (Chapter 3). The [R]E 24/7 model calculates the demand and supply by cluster. The electricity market in Costa Rica covers 99.4% of its territory and the majority of electricity generation is based on hydro power. Although the public power utility *Instituto Costarricense de Electricidad* (IEC) operates in a monopolistic structure, private operators that produce and distribute energy are allowed. Electricity demand is guaranteed by 2026 so ICE will not make more investments in the short or medium term. After that year, investments by ICE in wind and solar plants are planned (CND 2019)[55].Costa Rica's National Electric System (SEN) is divided into generation, transmission, and distribution equal to the structure of liberalised power markets and has eight electricity distributors. All systems of the SEN are interconnected within one single transmission system. Thus, the regional breakdown into seven regions for our power sector analysis focuses on future regional generation areas and the requirement to strengthen the distribution and transmission grid, whereas the overall interconnections between those regions are assumed to be established. Furthermore, we compare our load calculation results for 2017 with actual measured maximum loads in other published analyses such as CDN (2019) and ICE[56].

4.1 COSTA RICA: DEVELOPMENT OF POWER PLANT CAPACITIES

Costa Rica's current plans for the future development of the power capacities (GEP)[6] maintains a share of over 90% renewable electricity, but this will not be sufficient to supply the transport sector with additional power demand under a shift to electric mobility. Therefore, the transport sector will be increasingly dependent on imported oil and carbon emissions will continue to rise, even with a decarbonized power sector. The current installed power plant capacity is 3.5 GW, with a majority of hydro power (2.4 GW).

The capacity of solar photovoltaic and onshore wind will increase in all three scenarios. However, the solar photovoltaic market will vary significantly. While the annual average market until 2025 will range around only 3 MW per year under the REFERENCE scenario, RE1 will require an annual installation of 15 MW and the RE2 scenario 85 MW. However, after 2025, the solar photovoltaic market will grow substantially under all scenarios reflecting the cost advantages for solar systems. The wind market will increase significantly and will reach around 175 MW per year at the end of the modelling period – between 2040 and 2050. Almost all wind farms will be located in Guanacaste, the province with the most favourable wind resource. Furthermore, Costa Rica will increase its geothermal capacity, as projected under the *Generation Expansion Plan* (GEP)[6]. Additional bio-energy capacity will add to the diverse renewable power generation mix after 2025.

Table 30: Costa Rica—Average annual changes in installed power plant capacity

Power Generation: average annual change of installed capacity [MW/a]	2015–2025			2026–2035			2036–2050		
	REF	RE1	RE2	REF	RE1	RE2	REF	RE1	RE2
Oil/Diesel	57	3	−8	-	−9	−9	−42	-	-
Biomass	7	5	9	3	28	13	2	41	28
Hydro	55	58	7	-	-	-	-	-	-
Wind (onshore)	14	62	102	27	128	128	48	175	175
Photovoltaic (rooftop)	2	11	64	86	154	195	96	208	668
Photovoltaic (utility scale)	1	4	21	29	51	65	32	69	223
Geothermal	7	-	-	12	10	10	5	8	8
Renewable-fuel-based co-Generation	2	-	-	-	-	-	1	1	1

The annual installation rates for solar photovoltaic power must remain at around 200 MW between 2025 and 2035 in the RE1 scenario and 260 MW in the RE2 scenario. By 2035, the installation rates for wind power and solar power must reach 260 MW under the RE1 scenario and 900 MW under the RE2 scenario. Solar photovoltaics will be the key new additional renewable energy technology for Costa Rica,

[55] Government of Canada, Costa Rica Energy Sector Profile, Trade Commissioner, Adolfo Quesada, San Jose Costa Rica, website viewed in November 2019, https://www.tradecommissioner.gc.ca/costa-rica/market-reports-etudes-de-marches/0004212.aspx?lang=eng
[56] ICE, INDICE DE COBERTURA ELECTRICA, October 2017), https://www.grupoice.com/wps/wcm/connect/10261169-f251-465d-9b95-0b17c7baa49e/Cobertura+2013.pdf?MOD=AJPERES&attachment=false&id=1453148700496

but an improvement in the legislation for grid connection and installation is required to achieve these market volumes. However, diversity is required to maintain storage demand low and the security of supply high. All renewable power technologies—hydro power plants, bio energy, and geothermal power as well as on- and onshore wind—will be important for the successful decarbonization of Costa Rica's power sector.

4.2 COSTA RICA: UTILIZATION OF POWER GENERATION CAPACITIES

The division of Costa Rica into seven sub-regions reflects the provinces and the reporting of ICE's statistical data. The interconnection of the sub-regions according to the regional peak load over time is assumed. The resulting net transmission capacities are provided in section 4.4.

Table 31: Costa Rica—Installed photovoltaic and wind capacities by region in the RENEWABLES 1 scenario (2030)

RENEWABLES 1 2030	Alajuela	Cartago	Guanacaste	Heredia	Limon	Puntarenas	San Jose
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
Photovoltaic (rooftop)	180	95	69	92	80	87	271
Photovoltaic (utility scale)	45	24	17	23	20	22	68
Onshore wind	0	0	1,497	0	0	0	55

Table 32: Costa Rica—Installed photovoltaic and wind capacities by region in the RENEWABLES 2 scenario (2030)

RENEWABLES 2 2030	Alajuela	Cartago	Guanacaste	Heredia	Limon	Puntarenas	San Jose
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
Photovoltaic (rooftop)	122	65	47	63	55	59	182
Photovoltaic (utility scale)	31	16	12	16	14	15	45
Onshore wind	0	0	1,497	0	0	0	55

Table 33: Costa Rica—Installed photovoltaic and wind capacities by region in the RENEWABLES 2 scenario (2050)

RENEWABLES 2 2030	Alajuela	Cartago	Guanacaste	Heredia	Limon	Puntarenas	San Jose
	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]
Photovoltaic (rooftop)	2,125	1,124	812	1,085	951	1,030	3,158
Photovoltaic (utility scale)	531	281	203	271	238	258	789
Onshore wind	0	0	3,951	0	0	0	165

Table 31 and Table 32 show the installed capacities for solar photovoltaic and wind for the RE1 and RE2 scenarios, respectively, in 2030. The installed capacities for solar photovoltaic will be lower under the RE2 scenario in 2030 due to more-ambitious energy efficiency measures. However, after 2030, they will be significantly higher under the RE2 scenario. Table 33 shows the installed capacities in 2050. The wind capacities are almost entirely in Guanacaste under RE2 in 2050, and San Jose has the only other 165 MW of wind power. It is assumed that the wind farm will utilize large turbines, in the range of 8–10 MW each, to supply the metropolitan region of San Jose as a complementary power source for an otherwise solar-photovoltaic-dominated system. The distributions are based on the regional solar and wind

potentials and the regional demand, and aim to generate electricity where the demand is located. Whereas solar photovoltaic power generation is modular and can be installed close to the consumer or even integrated into buildings, onshore wind must be kept at a distance from settlements. Therefore, onshore wind must be clustered into wind farms with double digit megawatt capacities, on average.

Both RENEWABLE scenarios aim to achieve an even distribution of variable power plant capacities across all regions of Costa Rica by distributing the utility-scale solar photovoltaic plants accordingly. However, Guanacaste is Costa Rica's only regions with good wind resources, and will require both a significant increase in the transmission capacity to connect this region with all other regions in Costa Rica and higher storage capacities than other parts of the country. By 2030, variable power generation will reach 15%–20% in all regions and dispatch generation will remain at over 60%. The only exception will be Guanacaste, which will reach around 80% variable power generation by 2030, and will require grid expansion and enforcement.

The significant regional differences in the power system shares—the ratio between dispatchable and non-dispatchable variable power generation—will require a combination of increased interconnection, storage facilities, and demand-side management incentives. Over time, the proportion of variable power generation will increase (Table 34) under all scenarios. The regions with large utility-scale solar power plants and onshore wind capacities will have the highest shares of variable power generation in the grid and will require greater interconnection with neighbouring regions than those with smaller shares of variable electricity.

Table 34: **Costa Rica—Power system shares by technology group**

Power Generation Structure in percentage of annual supply [GWh/a]		REFERENCE			RENEWABLES 1			RENEWABLES 2		
Costa Rica		Variable Renewables	Dispatch Renewables	Dispatch Fossil	Variable Renewables	Dispatch Renewables	Dispatch Fossil	Variable Renewables	Dispatch Renewables	Dispatch Fossil
Alajuela	2015	4%	96%	0%	7%	92%	1%	7%	92%	1%
	2030	10%	76%	14%	11%	89%	0%	5%	95%	0%
	2050	31%	69%	0%	28%	72%	0%	57%	43%	0%
Cartago	2015	4%	96%	0%	11%	89%	0%	11%	89%	0%
	2030	9%	90%	0%	9%	91%	0%	6%	94%	0%
	2050	23%	77%	0%	23%	77%	0%	44%	56%	0%
Guanacaste	2015	11%	89%	0%	5%	95%	0%	5%	95%	0%
	2030	79%	21%	0%	85%	15%	0%	81%	19%	0%
	2050	92%	8%	0%	94%	6%	0%	95%	5%	0%
Heredia	2015	6%	94%	0%	9%	91%	0%	9%	91%	0%
	2030	12%	68%	20%	11%	89%	0%	6%	94%	0%
	2050	39%	61%	0%	31%	69%	0%	61%	39%	0%
Limon	2015	5%	95%	0%	15%	85%	0%	15%	85%	0%
	2030	11%	85%	4%	10%	90%	0%	6%	94%	0%
	2050	31%	69%	0%	28%	72%	0%	56%	44%	0%
Puntarenas	2015	2%	92%	6%	9%	91%	0%	9%	91%	0%
	2030	9%	66%	25%	13%	87%	0%	6%	94%	0%
	2050	36%	64%	0%	35%	65%	0%	65%	35%	0%
San Jose	2015	4%	96%	0%	13%	87%	0%	13%	87%	0%
	2030	11%	69%	20%	14%	86%	0%	8%	92%	0%
	2050	35%	65%	0%	33%	67%	0%	61%	39%	0%
Average	2015	5%	82%	1%	9%	79%	0%	9%	79%	0%
	2030	18%	60%	10%	19%	69%	0%	15%	73%	0%
	2050	36%	52%	0%	34%	53%	0%	55%	33%	0%

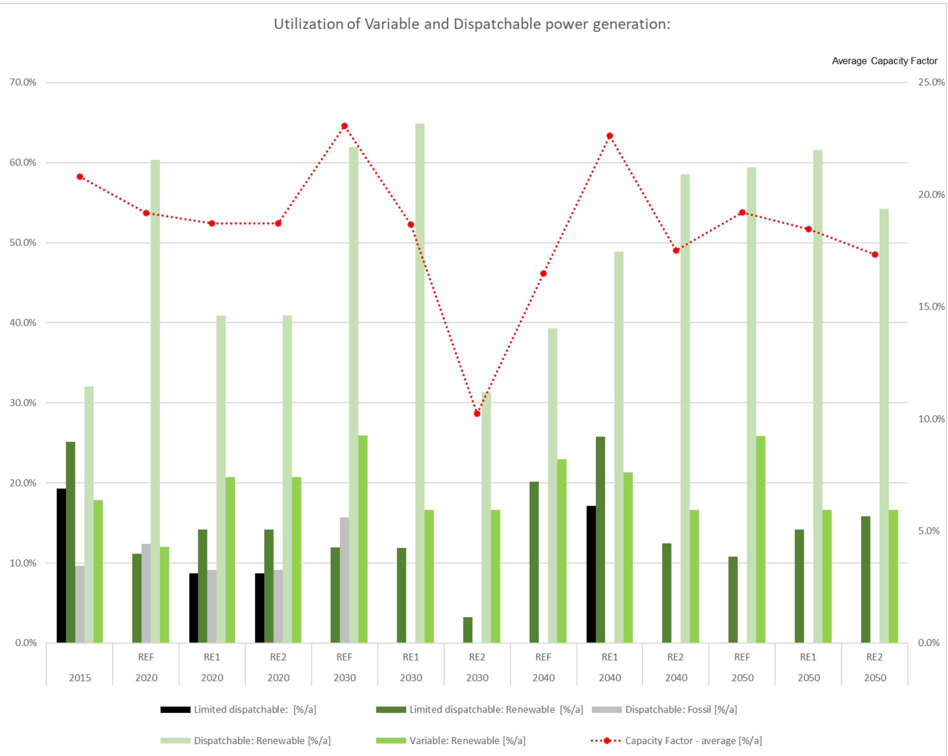
Table 35 shows the system-relevant technical characteristics of the various generation types. Future power systems must be structured according to the generation characteristics of each technology in order to maximize their synergy. Power utilities can encourage sector coupling—between industry, transport, and heating—in order to utilize various demand-side management possibilities and to maximize the cross-benefits. The integration of large shares of variable power generation will require a more flexible market framework. Power plants that require high capacity factors because of their technical limitations regarding flexibility ("base load power plants") might not be desirable for future power system operators. Therefore, capacity factors will become a technical characteristic rather than an economic necessity. Flexibility is a commodity that increases in value over time.

Table 35: Cost Rica—System-relevant generation types

Generation type	Fuel	Technology
Limited dispatchable	fossil, uranium	coal, brown coal/lignite, nuclear, (incl. co-generation)
	renewable	hydro power, bio-energy, geothermal, concentrated solar power (incl. co-generation)
Dispatchable	fossil	gas, oil, diesel (incl. co-generation)
		storage systems: batteries, pumped hydro power plants, hydrogen- and synthetic-fuelled power and co-generation plants
	renewable	bio-energy, hydro, hydrogen- and synthetic-fuelled power and co-generation plants
Variable	renewable	solar photovoltaic, onshore and offshore wind

Costa Rica's average capacity factors for the entire power plant fleet will remain at around 20% over the entire modelling period (red dotted line, Figure 26). The capacity factor for hydro power plants will operate on current capacity factors throughout all scenarios, although with significantly different installed capacities. During the uptake phase of variable renewables around 2025–2030, bio-energy-based generation will play a vital role in the security of supply and in fast-reacting dispatch power plants. Oil power plants will reach their peak capacity in 2020, and gradually be phased out by 2030 in both RENEWABLES scenarios. Geothermal power plants are assumed to operate stably and with limited dispatch capacity requirements, but will contribute ancillary services.

Figure 26: Costa Rica—Utilization of variable and dispatchable power generation



4.3 COSTA RICA: DEVELOPMENT OF LOAD, GENERATION, AND RESIDUAL LOAD

Table 36 shows that Costa Rica's average load is predicted to increase over the next decade by approximately 15% under the REFERENCE and RENEWABLES 1 scenarios, and by 27% under the RENEWABLES 2 scenario. The RE2 scenario will have the highest peak load by 2050, as a result of the increased electrification of the heating and transport sectors, whereas energy efficiency targets are more ambitious than under the RE1 scenario. The RE2 scenario has a stringent electrification strategy, especially in the transport sector, due to an earlier phase-out target for fossil fuels in the transport sector, but a more ambitious energy efficiency strategy. In comparison, the load for RE1 in 2050 is 1.5 GW higher than in the REF scenario, but 1.1 GW lower than under the RE2 scenario.

Table 36: Costa Rica—Projection of load, generation, and residual load until 2050

Costa Rica: Development of load and generation		REF				RE1				RE2			
		Max. Demand	Max. Generation	Max. Residual Load	Peak load increase	Max Demand	Max Generation	Max Residual Load	Peak load increase	Max Demand	Max Generation	Max Residual Load	Peak load increase
Costa Rica		[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]	[GW/h]	[GW/h]	[GW/h]	[%]
Alajuela	2020	0.4	0.3	0.2	100%	0.4	0.4	0.2	100%	0.5	0.5	0.1	100%
	2030	0.5	0.5	0.1	113%	0.6	0.5	0.2	128%	0.6	0.6	0.1	118%
	2050	0.7	0.7	0.3	165%	1.0	1.0	0.5	228%	1.2	2.4	0.8	231%
Cartago	2020	0.2	0.4	0.0	100%	0.2	0.4	0.0	100%	0.3	0.6	0.1	100%
	2030	0.2	0.5	0.0	113%	0.3	0.5	0.0	128%	0.3	0.6	0.0	118%
	2050	0.4	0.7	0.1	165%	0.5	0.8	0.0	228%	0.6	1.1	0.1	231%
Guanacaste	2020	0.2	0.3	0.0	100%	0.2	0.3	0.0	100%	0.2	0.3	0.1	100%
	2030	0.2	0.7	0.0	111%	0.2	1.5	0.1	126%	0.2	1.5	0.0	116%
	2050	0.2	1.8	0.1	151%	0.4	4.1	0.1	215%	0.4	4.6	0.2	220%
Heredia	2020	0.2	0.2	0.0	100%	0.2	0.2	0.1	100%	0.3	0.3	0.1	100%
	2030	0.2	0.2	0.1	111%	0.3	0.3	0.1	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.2	151%	0.5	0.5	0.2	215%	0.6	1.2	0.4	220%
Limon	2020	0.2	0.2	0.0	100%	0.2	0.3	0.0	100%	0.2	0.4	0.1	100%
	2030	0.2	0.2	0.0	111%	0.2	0.2	0.0	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.1	152%	0.4	0.5	0.2	216%	0.5	1.0	0.3	221%
Puntarenas	2020	0.2	0.2	0.0	100%	0.2	0.2	0.1	100%	0.3	0.3	0.1	100%
	2030	0.2	0.2	0.1	111%	0.3	0.2	0.1	126%	0.3	0.3	0.0	116%
	2050	0.3	0.4	0.2	152%	0.5	0.5	0.2	216%	0.6	1.2	0.4	221%
San Jose	2020	0.6	0.5	0.2	100%	0.6	0.6	0.2	100%	0.7	0.9	0.2	100%
	2030	0.7	0.7	0.2	130%	0.9	0.8	0.3	144%	1.0	1.0	0.1	131%
	2050	1.1	1.2	0.6	195%	1.6	1.6	0.8	259%	1.9	3.8	1.1	261%
Costa Rica	2020	2.0	2.2	0.6	100%	2.1	2.4	0.6	100%	2.5	3.3	0.7	100%
	2030	2.3	3.1	1.0	112%	2.7	4.1	1.0	127%	3.0	4.7	0.3	117%
	2050	3.3	5.4	2.0	156%	4.8	8.9	2.0	220%	5.9	15.3	3.1	224%

Although there are regional differences, the load increases (in percentages) across all regions will be quite similar. However, the actual loads will differ significantly between the regions. The lowest peak load will be in Guanacaste in 2050 with only 400 MW, whereas the maximum calculated generation capacity will reach 4,600 MW. However, the San Jose region will continue to have the highest peak load, at around 1,900 MW (RE2), whereas the maximum generation will be 3,800 MW—twice the maximum demand. This is an indication of the need to introduce energy efficiencies in parallel with the implementation of electric mobility to limit the required investment in upgrading Costa Rica's power grid infrastructure. However, under all scenarios and independent of the type of power generation, the power grid must by expanded over the next two decades, because increased electric mobility will require additional capacity in the power grid to accommodate the higher charging loads for vehicles. However, the locations of transmission grids will be dependent on the form of generation, because the locations of generation and the demand centres may differ for decentralized and centralized power generation.

4.4 COSTA RICA: DEVELOPMENT OF INTER-REGIONAL EXCHANGE OF CAPACITY

The increasing electricity load in all regions, shown in Table 36, will require an increase in the transmission and distribution networks in Costa Rica. This analysis assumes that those network upgrades will be implemented as the demand increases. Because it is a technical requirement, Costa Rica must increase its grid capacity proportionally to this increasing demand. This technical requirement to expand the grid capacity as the demand increases is largely independent of the type of power generation.

The inter-regional exchange of capacity is a function of the load development and the generation capacity in all seven regions. The [R]E 24/7 model distributes the generation capacity according to the regional load and the conditions for power generation. The locations of hydro- and geothermal power plants are fixed and the installation of new capacities will depend on geographic conditions and available water and geothermal resources. Solar power generation is more modular and can be distributed according to the load in the first place. However, as the share of renewable electricity increases, and the space available for utility-scale solar and onshore wind generation facilities and the availability and quality of local resources (such as solar radiation and/or wind speed) decrease, power might be generated further from its point of consumption. This will require more transmission capacity to exchange generation capacities between the seven regions of Costa Rica analysed here.

In our analysis, an increase in the necessary inter-regional exchange of capacity, in addition to the increase in grid capacity within the regions as demand increases, will start between 2025 and 2030. This is particularly for those regions with high population densities, high demand, and lower generation potential, such as San Jose. The main generation hub for renewable power in our analysis will the north-western region of Guanacaste (mainly wind power), followed by San Jose, which has significant capacities of both roof-top and utility-scale solar photovoltaic. Both regions will require significant increases in the transmission capacity to connect the generation and demand centres with each other.

The current actual interconnection capacities between the seven analysed regions were not available, so the modelling results are based on the assumptions described earlier. Furthermore, the transfer capacities for the REF scenario (Figure 27) and both alternative scenarios (Figure 28 and Figure 29) are only estimates because these capacities can be reduced by demand-side management measures, increased storage capacities, and variations in the actual distribution of power generation. The net transfer capacity in the REF scenario in 2050 will follows the same regional pattern as that in the two alternative scenarios. The modelling results indicate that interconnections must be built earlier in the alternative scenarios. The large solar capacities in the centre of the country and the concentration of dispatchable renewables in the north-west will require transmission capacities towards Costa Rica's demand centres.

Figure 27: Costa Rica—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to the load increase, under the REFERENCE scenario

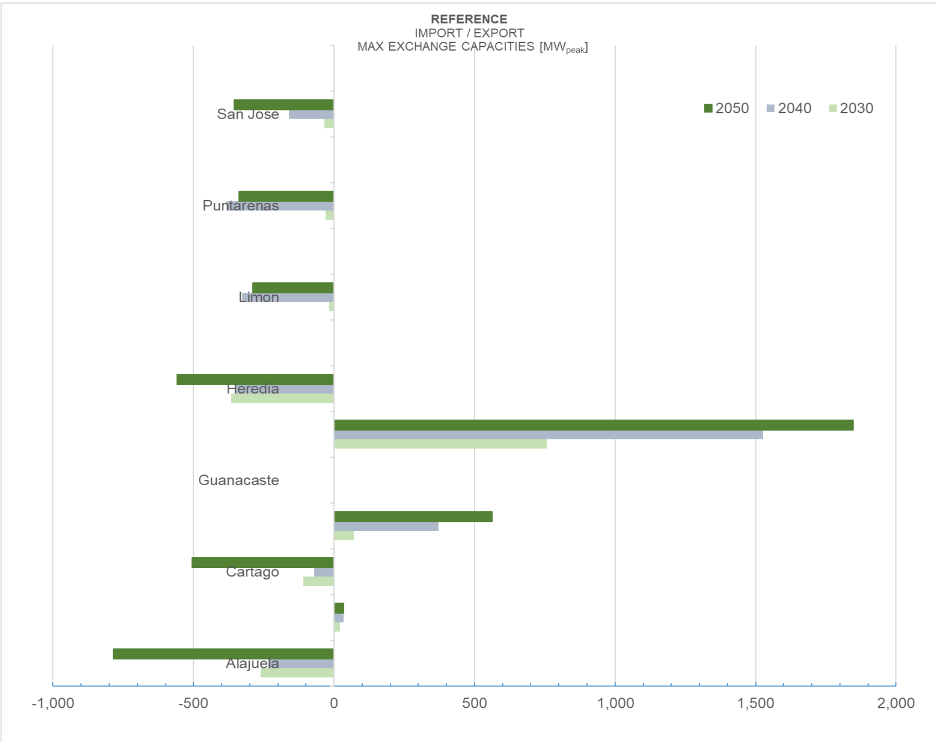


Figure 28: Costa Rica—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to the load increase, under the RENEWABLES 1 scenario

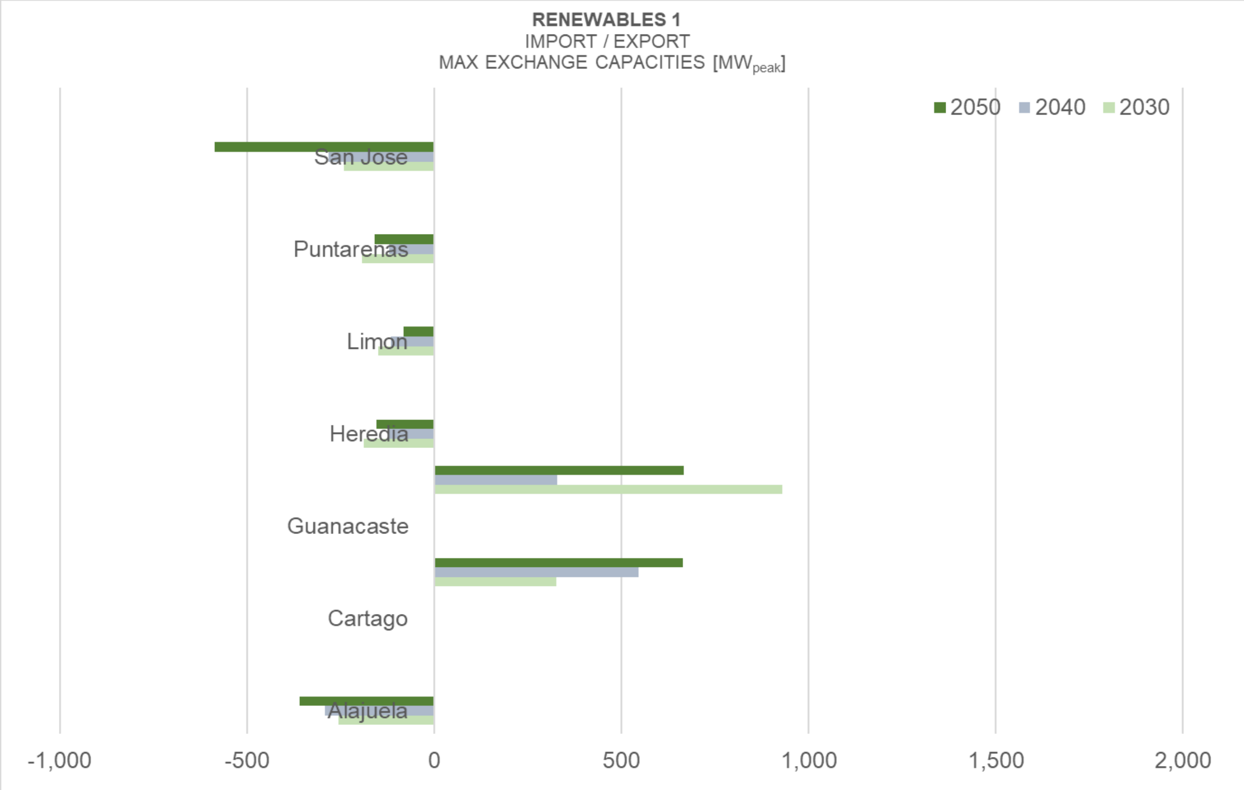


Figure 29: Costa Rica—Maximum inter-regional exchange capacities, additional to the required grid capacity expansion in response to the load increase, under the RENEWABLES 2 scenario

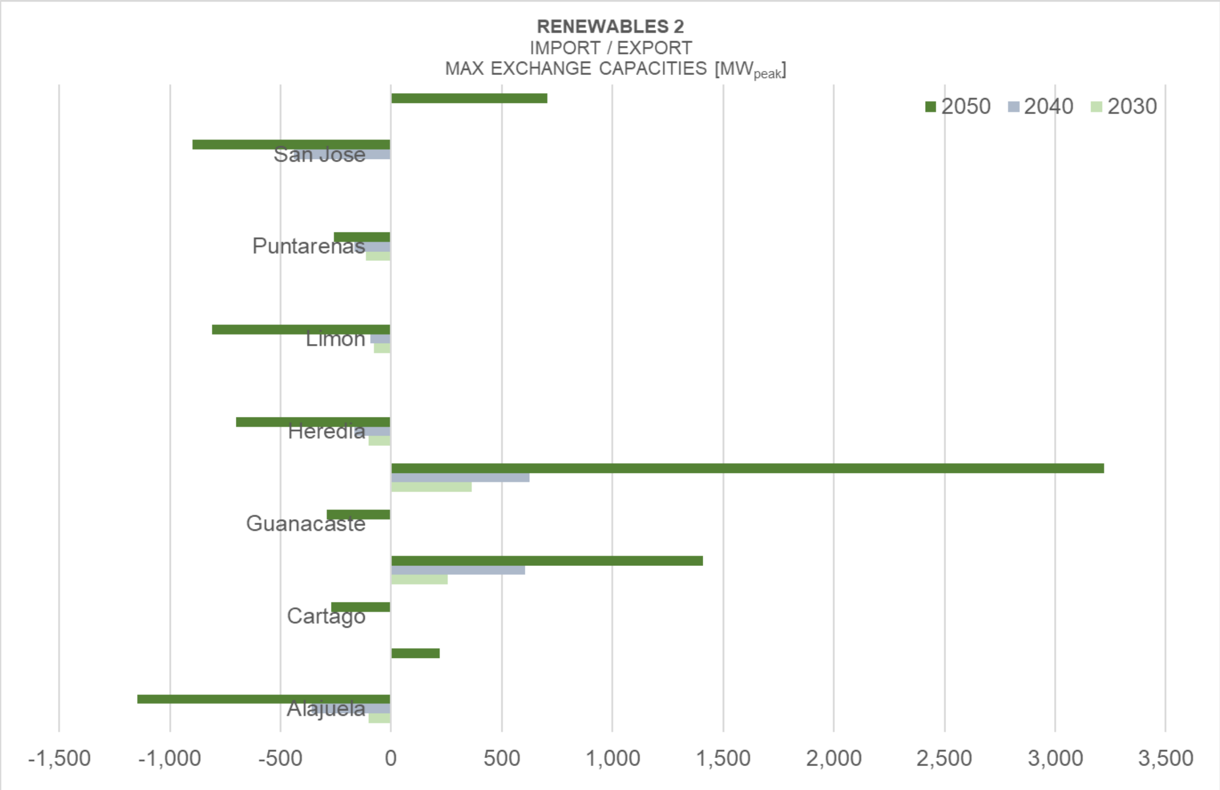
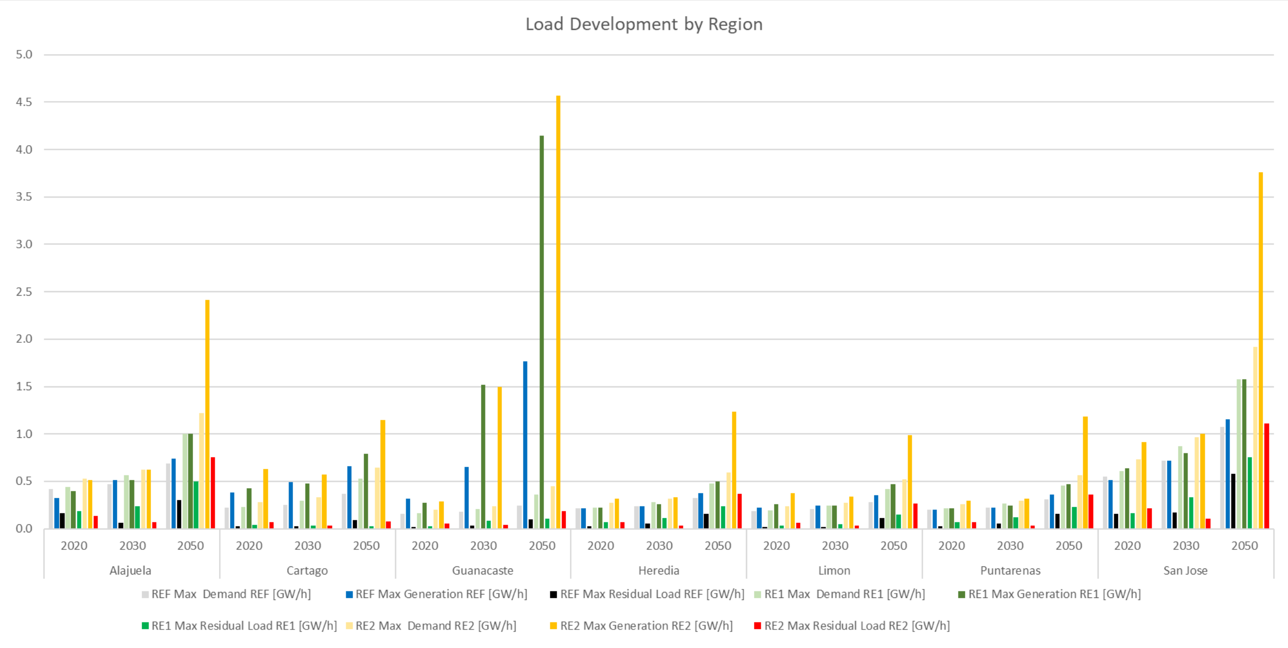


Figure 30: Costa Rica—Peak load and maximum generation development by region, in GW



The high-power demand of San Jose (see Table 36) reflects the significant industrial infrastructure around the capital and will continue to dominate the Costa Rican electricity market under all scenarios. However, the Alajuela region will grow substantially as well. Both RENEWABLES scenarios will have greater differences between peak generation and peak demand throughout the years, which is a consequence of power generation from variable sources. The development of the peak load, peak demand, and maximum residual load (the difference between demand and supply) for Costa Rica's seven sub-regions are shown in Figure 30.

Peak load and peak generation events do not appear at the same time, so the values cannot be simply summed. Moreover, the peak loads can vary across all regions and appear at different times. Therefore, to sum all the regional peak loads will only provide an indication of the peak load for the whole country. The maximum residual load[57] shows the maximum undersupply in a region and indicates the maximum load imported into that region. This event can only be several hours long, so the interconnection capacity might not be as high as the maximum residual load indicates. To optimize the interconnection for all regions was beyond the scope of this analysis. To guarantee the security of supply, the residual load of a region must be supplied by the following options:

- imports from other regions through interconnections;
- charged storage facilities providing additional load;
- available back-up capacities, such as gas peaking plants;
- load and demand-side management.

In practice, security of supply will be achieved with a combination of several measures and will require the in-depth analysis of regional technical possibilities, e.g., whether or not a cable connection is possible.

[57] Residual load is the load remaining after local generation within the analysed region is exhausted. There could be a shortage of load supply due to the operation and maintenance of a coal power plant or reduced output from wind and solar power plants.

4.5 STORAGE REQUIREMENTS

The quantity of the storage required is largely dependent on the storage costs, the grid expansion possibilities, and the generation mix itself. In terms of grid expansion, the geographic situation greatly influences the construction costs; crossing mountains, rivers, or swamps is significantly more expensive than crossing flat lands (Wendong 2016)[58]. Furthermore, the length of the permission process and whether people will be displaced by grid expansions may make storage economically preferable to grid expansion, even though the current transmission costs are lower per megawatt-hour than storage costs. Cebulla et al. (2018)[59] reported that “in general terms, PV-dominated grids directly correlate to high storage requirements, in both power capacity and energy capacity. Conversely, wind-dominated scenarios require significantly lower storage power and energy capacities, if grid expansion is unlimited or cheap”.

Under all scenarios, the share of variable generation will not exceed 30% by 2030 in any region, except in Guanacaste, where the share will already be around 80%.

Table 38 shows the storage and dispatch requirements to avoid curtailment under both the RENEWABLE and REFERENCE scenarios. The table identifies the capacity (= storage volume) in gigawatt hours (GWh/a) per year and the required annual through-put capacity of the storage system. It also shows the installed capacity required to avoid curtailment, in terms of the load in gigawatts (GW). These results are consistent with the findings of Cebulla et al., with 4,200 MW storage required in RE1 by 2050 and 10,000 MW in RE2. The solar capacity in relation to the wind capacity is significantly higher in RE2 than in RE1 or the REFERENCE scenario.

However, there is no “hard number” for storage requirements because they are dependent upon the available dispatch capacity (e.g., from [bio-]gas power plants) and the possibility of demand-side management. The optimally economic storage capacity, in terms of both the overall storage volume and the installed capacity, is also a function of the storage costs, the wind and solar generation costs, and the power system requirements.

Over the past decade, the cost of batteries, especially lithium batteries, has declined significantly. However, solar photovoltaic costs have also declined significantly. Storage is economic when the cost per kilowatt-hour is equal to or lower than the cost of generation. Therefore, if storage costs are high, curtailment could be economic. However, there are various reasons for curtailment, including transmission constraints, system balancing, and economic reasons (NREL 2014)[60]. The California Independent System Operator (CISO)[61] defines economic curtailment during times of oversupply as a market-based decision. “During times of oversupply, the bulk energy market first competitively selects the lowest cost power resources. Renewable resources can “bid” into the market in a way to reduce production when prices begin to fall. This is a normal and healthy market outcome. Then, self-scheduled cuts are triggered and prioritized using operational and tariff considerations. Economic curtailments and self-scheduled cuts are considered “market-based” (end of quote).

In this analysis, we assume that a curtailment rate of 5% in the annual generation (in GWh/a) for solar photovoltaic and onshore and offshore wind will be economically viable by 2030. By 2050, we assume an “economic curtailment rate” of 10%. However, economic curtailment rates are dependent on the available grid capacities and can vary significantly, even within Costa Rica. Curtailment will be economic when the power generated from a wind turbine or photovoltaic power plant exceeds the demand for only a few hours per day and this event occurs rarely across the year. Therefore, grid expansion will not be justifiable. Table 37 shows the storage required to avoid curtailment, or in other words, the entire surplus generation at any given time, by region and under all three scenarios.

[58] Wendong (2016), Wei, Wendong et al. Regional study on investment for transmission infrastructure in China based on the State Grid data,10.1007/s11707-016-0581-4, Frontiers of Earth Science, June 2016

[59] Cebulla et. al. (2018), How much electrical energy storage do we need? A synthesis for the U.S., Europe, and Germany, Journal of Cleaner Production, February 2018, https://www.researchgate.net/publication/322911171_How_much_electrical_energy_storage_do_we_need_A_synthesis_for_the_US_Europe_and_Germany/link/5a782bb50f7e9b41dbd26c20/download

[60] Wind and Solar Energy Curtailment: Experience and Practices in the United States; Lori Bird, Jaquelin Cochran, and Xi Wang, National Renewable Energy Laboratory (NREL), March 2014, https://www.nrel.gov/docs/fy14osti/60983.pdf

[61] Impacts of renewable energy on grid operations, factsheet, https://www.caiso.com/Documents/CurtailmentFastFacts.pdf

Table 37: Costa Rica—Storage requirements to avoid curtailment

Storage requirement to avoid curtailment		REF		RE1		RE2	
		Required storage to avoid curtailment (Overproduction)	Required storage capacity to avoid curtailment	Required storage to avoid curtailment (Overproduction)	Required storage capacity to avoid curtailment	Required storage to avoid curtailment (Overproduction)	Required storage capacity to avoid curtailment
Costa Rica		[GWh/a]	[GW/a]	[GWh/a]	[GW/a]	[GWh/a]	[GW/a]
Alajuela	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	4.328	0.142	3.636	0.097	999.796	1.353
Cartago	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	1.913	0.078	0.000	0.000	518.813	0.583
Guanacaste	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	804.930	0.502	1066.670	1.361	994.825	1.352
	2050	3,042.331	1.551	3719.743	3.843	4089.552	4.180
Heredia	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	12.018	0.104	5.744	0.086	573.602	0.723
Limon	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	6.240	0.095	0.692	0.030	503.973	0.534
Puntarenas	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	4.760	0.115	7.129	0.077	651.348	0.691
San Jose	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	7.697	0.257	0.512	0.079	976.311	2.010
Total	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	804.930	0.502	1066.670	1.361	994.825	1.352
	2050	3079.288	2.342	3737.457	4.212	8313.395	10.074

The REFERENCE scenario requires the lowest storage capacity for Costa Rica, with the majority concentrated in the wind-dominated region. The oversupply in the north-west region will result from the high installed capacity (relative to the local load) of onshore wind. The RE1 scenario will lead to a storage capacity around 2.5 times higher than the REFERENCE scenario, all of which is in Guanacaste. By 2030, only one region will require storage under all scenarios, whereas by 2040, storage will be required in all seven regions.

The storage requirements have been assessed based on the assumptions that all the regions will have established interconnection capacities, as indicated in section 4.3, and that the economic curtailment rates are fully exhausted.

Table 38: Costa Rica—Estimated electricity storage requirements for both RENEWABLES scenarios

Storage requirement to avoid curtailment		REF		RE1		RE2	
		Total storage throughput	Storage capacity (1)	Total storage throughput	Storage capacity (1)	Total storage throughput	Storage capacity (1)
Costa Rica		[GWh/a	[GW/a]	[GWh/a]	[GW/a]	[GWh/a]	[GW/a]
Alajuela	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	8.657	0.007	7.261	0.006	140.446	0.117
Cartago	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	3.826	0.003	0.000	0.000	80.407	0.067
Guanacaste	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	13.906	0.012	10.666	0.009	11.088	0.009
	2050	50.143	0.042	43.639	0.036	51.491	0.043
Heredia	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	23.028	0.019	9.997	0.008	78.406	0.065
Limon	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	12.000	0.010	1.384	0.001	71.035	0.059
Puntarenas	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	9.051	0.008	12.572	0.010	81.067	0.068
San Jose	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	0.000	0.000	0.000	0.000	0.000	0.000
	2050	15.176	0.013	1.025	0.001	215.837	0.180
Total	2020	0.000	0.000	0.000	0.000	0.000	0.000
	2030	13.906	0.012	10.666	0.009	11.088	0.009
	2050	121.881	0.102	75.878	0.063	718.690	0.599

(1) Calculated with an average capacity factor of 1,200 hours per year

The estimates provided for the storage requirements also presuppose that variable renewables are first in the dispatch order, ahead all other types of power generation. Priority dispatch is the economic basis for investment in utility-scale solar photovoltaic and wind projects. The curtailment rates or storage rates will be significantly higher with the priority dispatch of other types of power. This case has not been calculated because it would involve a lack of investment in solar and wind in the first place. With decreasing storage costs, as projected by Bloomberg (2019)[62], interconnections might become less economically favourable than batteries. This would increase even further the economic advantage of decentralized solar photovoltaics close to the electricity demand over centralized coal or gas power plants concentrated in the north and south of the country.

Table 38 gives an overview of the estimated storage capacity requirements for both RENEWABLES scenarios. The majority of storage facilities will be required in Guanacaste because this region has Costa Rica's largest wind resources and a significant proportion of wind generation will be concentrated here. For the whole of Costa Rica, the required estimated storage capacity will be 1.0% of the total variable generation in 2050 under the RE1 scenario, and 3.5% under the RE2 scenario. However, there will be

[62] Bloomberg (2019), A Behind the Scenes Take on Lithium-ion Battery Prices, Logan Goldi-Scot, BloombergNEF, March 5 2019, https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/

significant regional differences. To remain within the economic curtailment range, storage will be required in all regions under both scenarios. For the whole of Costa Rica, the simulation of the renewable power generation under scenarios RE1 and RE2 leads to storage requirements of 76 GWh/a and 719 GWh/a, respectively, with installed input/output capacities of 60–100 MW and around 600 MW, respectively. The requirement for utility-scale storage will occur by 2030. The storage demand will vary significantly and will be a function of the regional distribution of variable power generation and the extent to which the regions can exchange load via interconnections. The storage capacity in electric vehicles is not included in this calculation and is assumed to be used for load management via charging strategies, but not as storage capacities for stationary power system requirements.

4.6 SUMMARY: POWER SECTOR ANALYSIS FOR COSTA RICA

Both RENEWABLES scenarios prioritize the use of Costa Rica's renewable energy resources to reduce its dependence on oil imports for the growing transport demand with electrification. Costa Rica will significantly increase its power demand under each power generation scenario. Therefore, power grids must expand, and power generation must increase as the load increases, under all scenarios.

However, the electrification of the transport sector in combination with renewable-energy-dominated power generation will require a different infrastructural design than the oil-dominated transport sector. To harvest Costa Rica's onshore wind and solar resources, as well as its geothermal and bio-energy potential, the power grid must be able to transport large loads from the west coast further inland, whereas decentralized power will shoulder a significant part of the residential sector demand. Onshore wind will require transmission lines to the load centres of Costa Rica.

In 2050, the majority of system services (ancillary and dispatch) power will come from bio-energy, geothermal power, and hydro power, which may be operated with on-site storage technologies after 2030. Costa Rica has abundant renewable energy resources, which could supply, with the currently available technologies, all the renewable electricity required to power the traditional power sector and shoulder the increased electricity demand for electric vehicles. However, more research is required to assess how electric mobility can be integrated into the power sector to provide load and demand management and to use storage capacities as efficiently as possible.

5 APPENDIX

5.1 RESULTS Table 39: Results for the long-term energy scenario in all sectors - Costa Rica - REFERENCE

Electricity generation [TWh/a]	2012	2015	2020	2030	2040	2050
Power plants	10	11	13	15	17	21
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	1	0	1	1	1	1
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0
- Hydro	7	8	9	9	9	9
- Wind	1	1	1	2	3	5
of which wind offshore	0	0	0	0	0	1
- PV	0	0	0	1	2	4
- Geothermal	1	1	1	2	2	2
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
CHP by producer						
- Main activity producers	0	0	0	0	0	0
- Autoproducers	0	0	0	0	0	0
Total generation	10	11	13	15	18	21
- Fossil	1	0	1	1	1	1
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	1	0	1	1	1	1
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
- of which renewable H2	0	0	0	0	0	0
- Renewables (w/o renewable hydrogen)	9	11	12	14	16	20
- Hydro	7	8	9	9	9	9
- Wind	1	1	1	2	3	5
- PV	0	0	0	1	2	4
- Biomass (& renewable waste)	0	0	0	0	0	0
- Geothermal	1	1	1	2	2	2
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Distribution losses	1	1	1	2	2	2
Own consumption electricity	0	0	0	0	0	0
Electricity for hydrogen production	0	0	0	0	0	0
Electricity for synfuel production	0	0	0	0	0	0
Final energy consumption (electricity)	9	9	11	13	15	18
Variable RES (PV, Wind, Ocean)	1	1	1	3	5	8
Share of variable RES	5%	10%	11%	17%	29%	39%
RES share (domestic generation)	92%	99%	92%	90%	94%	95%

Transport - Final Energy [PJ/a]	2012	2015	2020	2030	2040	2050
road	66	74	83	103	126	159
- fossil fuels	66	74	82	101	123	155
- biofuels	0	0	1	1	2	2
- synfuels	0	0	0	0	0	0
- natural gas	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0
- electricity	0	0	0	0	1	2
rail	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
- electricity	0	0	0	0	0	0
navigation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
aviation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
total (incl. pipelines)	66	74	91	110	133	165
- fossil fuels	66	74	82	101	124	156
- biofuels (incl. biogas)	0	0	1	1	2	2
- synfuels	0	0	0	0	0	0
- natural gas	0	0	8	7	7	6
- hydrogen	0	0	0	0	0	0
- electricity	0	0	0	0	1	2
total RES	0	0	1	2	2	3
RES share	0%	0%	2%	2%	2%	2%

Heat supply and air conditioning [PJ/a]	2012	2015	2020	2030	2040	2050
District heating plants	0	0	2	2	3	3
- Fossil fuels	0	0	0	0	0	0
- Biomass	0	0	2	2	2	2
- Solar collectors	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
Heat from CHP 1)	1	1	1	1	2	2
- Fossil fuels	0	0	0	0	0	0
- Biomass	1	1	1	1	1	2
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
Direct heating	33	34	41	52	91	114
- Fossil fuels	14	14	17	21	52	61
- Biomass	19	19	22	29	37	49
- Solar collectors	0	0	0	0	0	0
- Geothermal	0	0	1	1	1	1
- Heat pumps 2)	0	0	0	0	1	1
- Electric direct heating	0	1	1	1	1	2
- Hydrogen	0	0	0	0	0	0
Total heat supply3)	34	35	44	56	96	119
- Fossil fuels	14	14	17	21	52	61
- Biomass	20	20	25	32	40	53
- Solar collectors	0	0	0	1	1	1
- Geothermal	0	0	1	1	1	2
- Heat pumps 2)	0	0	0	0	1	1
- Electric direct heating	0	1	1	1	1	2
- Hydrogen	0	0	0	0	0	0
RES share (including RES electricity)	59%	60%	61%	62%	45%	48%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.1	0.2	0.3

Installed Capacity [GW]	2012	2015	2020	2030	2040	2050
Total generation	3	3	4	4	6	7
- Fossil	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants	0	0	0	0	0	0
- Renewables	2	3	3	4	5	7
- Hydro	2	2	2	2	2	2
- Wind	0	0	0	0	1	1
of which wind offshore	0	0	0	0	0	0
- PV	0	0	0	1	2	2
- Biomass (& renewable waste)	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	0	0	1	2	4
Share of variable RES	10%	18%	12%	25%	41%	53%
RES share (domestic generation)	87%	98%	86%	89%	91%	93%

Final Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total (incl. non-Energy use)	145	156	182	229	303	366
Total Energy use 1)	142	153	179	226	300	362
Transport	66	74	87	114	139	170
- Oil products	66	74	85	112	136	166
- Natural gas	0	0	0	0	0	0
- Biofuels	0	0	1	1	2	2
- Synfuels	0	0	0	0	0	0
- Electricity	0	0	1	1	2	2
RES electricity	0	0	1	1	2	2
- Hydrogen	0	0	0	0	0	0
RES share Transport	0%	0%	2%	2%	2%	2%
Industry	36	38	44	55	67	81
- Electricity	7	7	8	9	10	13
RES electricity	6	7	7	8	10	12
- Public district heat	0	1	1	2	2	2
RES district heat	0	1	1	1	1	2
- Hard coal & lignite	1	1	1	1	1	0
- Oil products	10	10	10	6	2	2
- Gas	1	1	1	7	15	18
- Solar	0	0	0	0	0	0
- Biomass	17	19	22	29	35	44
- Geothermal	0	0	1	1	1	2
- Hydrogen	0	0	0	0	0	0
RES share Industry	65%	70%	70%	72%	72%	74%
Other Sectors	40	40	48	57	94	112
- Electricity	26	27	31	36	42	51
RES electricity	24	27	29	33	39	49
- Public district heat	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0
- Hard coal & lignite	0	0	0	0	0	0
- Oil products	6	7	9	12	14	17
- Gas	0	0	0	0	27	30
- Solar	0	0	0	0	0	0
- Biomass	8	6	7	9	11	14
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
RES share Other Sectors	79%	82%	75%	73%	54%	56%
Total RES	55	60	69	84	102	126
RES share	39%	39%	38%	37%	34%	35%
Non energy use	2	3	3	3	3	3
- Oil	2	3	3	3	3	3
- Gas	0	0	0	0	0	0
- Coal	0	0	0	0	0	0

Energy-Releated CO2 Emissions [Million tons/a]	2012	2015	2020	2030	2040	2050
Condensation power plants	1	0	1	1	1	1
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil + Diesel	1	0	1	1	1	1
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
CO2 emissions power and CHP plants	1	0	1	1	1	1
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil + Diesel	1	0	1	1	1	1
CO2 intensity (g/kWh)	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0
- CO2 intensity fossil electr. generation	760	760	759	759	759	757
- CO2 intensity total electr. generation	63	8	61	75	45	34
CO2 emissions by sector	7	8	10	13	16	19
- % of 1990 emissions (Mill t)	53%	54%	70%	89%	114%	134%
- Industry 1)	1	1	1	1	1	1
- Other sectors 1)	0	1	1	1	3	3
- Transport	5	6	6	8	10	12
- Power generation 2)	1	0	1	1	1	1
- Other conversion 3)	0	1	1	1	1	2
Population (Mill.)	5	5	5	5	6	6
CO2 emissions per capita (t/capita)	2	2	2	2	3	3

Primary Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total	177	184	240	298	376	437
- Fossil	96	98	139	175	229	265
- Hard coal	3	3	3	3	3	1
- Lignite	0	0	0	0	0	0
- Natural gas	0	0	9	15	53	55
- Crude oil	93	95	128	158	174	209
- Nuclear	0	0	0	0	0	0
- Renewables	81	86	101	123	147	173
- Hydro	26	29	32	32	32	32
- Wind	2	4	5	6	10	17
- Solar	0	0	1	3	8	13
- Biomass (& renewable waste)	28	28	37	48	57	69
- Geothermal	25	25	27	33	39	41
- Ocean energy	0	0	0	0	0	0
- of which non-energy use	2	3	3	3	3	3
Total RES	81	86	99	121	146	173
RES share	46%	47%	42%	41%	39%	39%

Table 40: Results for the long-term energy scenario in all sectors—Costa Rica - RENEWABLES 1

Electricity generation [TWh/a]	2012	2015	2020	2030	2040	2050
Power plants	10	11	12	17	24	34
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	1	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	1	2	4
- Hydro	7	8	9	9	9	9
- Wind	1	1	2	4	7	12
of which wind offshore	0	0	0	0	0	0
- PV	0	0	0	1	4	7
- Geothermal	1	1	1	2	2	3
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
CHP by producer						
- Main activity producers	0	0	0	0	0	0
- Autoproducers	0	0	0	0	0	0
Total generation	10	11	12	17	24	34
- Fossil	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	1	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
- of which renewable H2	0	0	0	0	0	0
- Renewables (w/o renewable hydrogen)	9	11	12	17	24	34
- Hydro	7	8	9	9	9	9
- Wind	1	1	2	4	7	12
- PV	0	0	0	1	4	7
- Biomass (& renewable waste)	0	0	0	1	2	4
- Geothermal	1	1	1	2	2	3
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Distribution losses	1	1	1	2	3	4
Own consumption electricity	0	0	0	0	0	0
Electricity for hydrogen production	0	0	0	0	0	0
Electricity for synfuel production	0	0	0	0	0	0
Final energy consumption (electricity)	9	9	11	15	22	30
Variable RES (PV, Wind, Ocean)	1	1	2	6	11	18
Share of variable RES	5%	10%	15%	33%	44%	54%
RES share (domestic generation)	92%	99%	99%	100%	100%	100%

Transport - Final Energy [PJ/a]	2012	2015	2020	2030	2040	2050
road	66	74	82	90	97	110
- fossil fuels	66	74	82	80	75	73
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
- natural gas	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0
- electricity	0	0	1	10	22	36
rail	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
- electricity	0	0	0	0	0	0
navigation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
aviation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
total (incl. pipelines)	66	74	82	90	97	110
- fossil fuels	66	74	82	80	76	73
- biofuels (incl. biogas)	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
- natural gas	0	0	0	0	0	0
- hydrogen	0	0	0	0	0	0
- electricity	0	0	1	10	22	36
total RES	0	0	1	10	22	36
RES share	0%	0%	2%	12%	23%	34%

Heat supply and air conditioning [PJ/a]	2012	2015	2020	2030	2040	2050
District heating plants	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0
- Solar collectors	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
Heat from CHP 1)	1	1	1	1	1	2
- Fossil fuels	1	1	0	0	0	0
- Biomass	0	0	1	1	1	1
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
Direct heating	33	34	42	48	84	104
- Fossil fuels	14	14	17	4	0	0
- Biomass	19	19	23	37	61	63
- Solar collectors	0	0	0	2	8	15
- Geothermal	0	0	0	1	3	5
- Heat pumps 2)	0	0	0	1	5	10
- Electric direct heating	0	1	1	3	6	11
- Hydrogen	0	0	0	0	0	0
Total heat supply3)	34	35	43	50	85	106
- Fossil fuels	15	15	17	5	1	0
- Biomass	19	19	25	38	62	64
- Solar collectors	0	0	0	2	8	15
- Geothermal	0	0	0	1	3	5
- Heat pumps 2)	0	0	0	1	5	10
- Electric direct heating 2)	0	1	1	3	6	11
- Hydrogen	0	0	0	0	0	0
RES share (including RES electricity)	56%	57%	61%	91%	99%	100%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.0	0.0	0.0	0.0

Installed Capacity [GW]	2012	2015	2020	2030	2040	2050
Total generation	3	3	3	5	8	13
- Fossil	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	0	0
- Oil	0.326	0.042	0.068	0.000	0.000	0.000
- Diesel	0.000	0.000	0.000	0.000	0.000	0.000
- Nuclear	0	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants	0	0	0	0	0	0
- Renewables	2	3	3	5	8	13
- Hydro	2	2	2	2	2	2
- Wind	0	0	1	2	3	4
of which wind offshore	0	0	0	0	0	0
- PV	0	0	0	1	3	5
- Biomass (& renewable waste)	0.040	0.040	0.033	0.167	0.403	0.793
- Geothermal	0	0	0	0	0	0
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	0	1	3	5	9
Share of variable RES	10%	18%	23%	49%	63%	72%
RES share (domestic generation)	87%	98%	98%	100%	100%	100%

Final Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total (incl. non-energy use)	144	156	178	197	249	288
Total energy use 1)	142	153	175	194	247	286
Transport	66	74	83	90	97	110
- Oil products	66	74	82	80	76	74
- Natural gas	0	0	0	0	0	0
- Biofuels	0	0	0	0	0	0
- Synfuels	0	0	0	0	0	0
- Electricity	0	0	1	10	22	36
RES electricity	0	0	1	10	22	36
- Hydrogen	0	0	0	0	0	0
RES share Transport	0%	0%	2%	12%	23%	34%
Industry	36	38	44	51	62	74
- Electricity	7	7	8	10	15	22
RES electricity	6	7	8	10	15	22
- Public district heat	0	1	0	0	0	0
RES district heat	0	1	0	0	0	0
- Hard coal & lignite	1	1	1	0	0	0
- Oil products	10	9	11	2	0	0
- Gas	1	1	1	1	0	0
- Solar	0	0	0	1	2	6
- Biomass	17	19	24	36	44	46
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
RES share Industry	66%	70%	71%	93%	99%	100%
Other Sectors	40	40	48	53	88	102
- Electricity	26	27	31	35	41	51
RES electricity	24	27	31	35	41	51
- Public district heat	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0
- Hard coal & lignite	0	0	0	0	0	0
- Oil products	6	7	9	3	1	1
- Gas	0	0	0	0	0	0
- Solar	0	0	0	1	6	10
- Biomass	8	6	8	13	34	28
- Geothermal	0	0	0	2	7	13
- Hydrogen	0	0	0	0	0	0
RES share Other Sectors	79%	82%	81%	95%	99%	99%
Total RES	55	60	71	108	171	213
RES share	39%	39%	41%	56%	69%	74%
Non energy use	2	3	3	2	2	2
- Oil	2	3	3	2	2	2
- Gas	0	0	0	0	0	0
- Coal	0	0	0	0	0	0

Energy-Releated CO2 Emissions [Million tons/a]	2012	2015	2020	2030	2040	2050
Condensation power plants	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil + Diesel	1	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
CO2 emissions power and CHP plants	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil & diesel	1	0	0	0	0	0
CO2 intensity (g/kWh)	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0
- CO2 intensity fossil electr. generation	760	760	760	779	779	779
- CO2 intensity total electr. generation	760	760	760	779	779	779
CO2 emissions by sector	7	8	9	7	6	6
- % of 1990 emissions (Mill t)	53%	54%	62%	51%	45%	43%
- Industry 1)	1	1	1	0	0	0
- Other sectors 1)	0	1	1	0	0	0
- Transport	5	6	6	6	6	6
- Power generation 2)	1	0.09	0.08	0.02	0.01	0.01
- Other conversion 3)	0	1	1	1	0	0
Population (Mill.)	5	5	5	5	6	6
CO2 emissions per capita (t/capita)	2	2	2	1	1	1

Primary Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total	177	184	228	246	315	372
- Fossil	96	98	116	95	84	81
- Hard coal (& non-renewable waste)	3	3	1	0	0	0
- Lignite	0	0	0	0	0	0
- Natural gas	0	0	2	2	1	1
- Crude oil	93	95	113	93	82	80
- Nuclear	0	0	0	0	0	0
- Renewables	81	86	112	151	231	291
- Hydro	26	29	32	33	33	33
- Wind	2	4	7	15	26	42
- Solar	0	0	0	8	21	39
- Biomass (& renewable waste)	28	28	34	59	102	118
- Geothermal	25	25	39	36	50	60
- Ocean energy	0	0	0	0	0	0
- of which non-energy use	2	3	3	2	2	2
Total RES	81	86	112	151	231	291
RES share	46%	47%	49%	61%	73%	78%

Table 41: Results for the long-term energy scenario in all sectors—Costa Rica - RENEWABLES 2

Electricity generation [TWh/a]	2012	2015	2020	2030	2040	2050
Power plants	10	11	12	16	26	43
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	1	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	1	3
- Hydro	7	8	9	9	9	9
- Wind	1	1	2	4	7	12
of which wind offshore	0	0	0	0	0	0
- PV	0	0	0	1	6	17
- Geothermal	1	1	1	2	2	3
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
of which from H2	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
- Biomass (& renewable waste)	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
CHP by producer						
- Main activity producers	0	0	0	0	0	0
- Autoproducers	0	0	0	0	0	0
Total generation	10	11	13	16	26	43
- Fossil	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	1	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
- of which renewable H2	0	0	0	0	0	0
- Renewables (w/o renewable hydrogen)	9	11	12	16	26	43
- Hydro	7	8	9	9	9	9
- Wind	1	1	2	4	7	12
- PV	0	0	0	1	6	17
- Biomass (& renewable waste)	0	0	0	1	2	3
- Geothermal	1	1	1	2	2	3
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Distribution losses	1	1	1	2	3	5
Own consumption electricity	0	0	0	0	0	0
Electricity for hydrogen production	0	0	0	0	0	0
Electricity for synfuel production	0	0	0	0	0	0
Final energy consumption (electricity)	9	9	11	15	23	38
Variable RES (PV, Wind, Ocean)	1	1	2	5	13	28
Share of variable RES	5%	10%	15%	31%	51%	66%
RES share (domestic generation)	92%	99%	99%	100%	100%	100%

Transport - Final Energy [PJ/a]	2012	2015	2020	2030	2040	2050
road	66	74	82	88	83	72
- fossil fuels	66	74	82	75	48	0
- biofuels	0	0	0	6	11	15
- synfuels	0	0	0	0	0	0
- natural gas	0	0	0	0	1	0
- hydrogen	0	0	0	0	0	0
- electricity	0	0	1	7	24	56
rail	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
- electricity	0	0	0	0	0	0
navigation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
aviation	0	0	0	0	0	0
- fossil fuels	0	0	0	0	0	0
- biofuels	0	0	0	0	0	0
- synfuels	0	0	0	0	0	0
total (incl. pipelines)	66	74	82	88	83	72
- fossil fuels	66	74	82	75	48	0
- biofuels (incl. biogas)	0	0	0	6	11	16
- synfuels	0	0	0	0	0	0
- natural gas	0	0	0	0	1	0
- hydrogen	0	0	0	0	0	0
- electricity	0	0	1	7	24	56
total RES	0	0	1	13	35	72
RES share	0%	0%	1%	15%	42%	100%

Heat supply and air conditioning [PJ/a]	2012	2015	2020	2030	2040	2050
District heating plants	0	0	0	0	0	0
- Fossil fuels	0	0	0	0	0	0
- Biomass	0	0	0	0	0	0
- Solar collectors	0	0	0	0	0	0
- Geothermal	0	0	0	0	0	0
Heat from CHP 1)	1	1	1	1	2	2
- Fossil fuels	1	1	0	0	0	0
- Biomass	0	0	1	1	1	2
- Geothermal	0	0	0	0	0	0
- Hydrogen	0	0	0	0	0	0
Direct heating	33	34	42	48	84	104
- Fossil fuels	14	14	16	4	0	0
- Biomass	19	19	23	34	52	44
- Solar collectors	0	0	0	2	8	15
- Geothermal	0	0	0	1	3	5
- Heat pumps 2)	0	0	1	3	10	21
- Electric direct heating	0	1	1	3	10	18
- Hydrogen	0	0	0	0	0	0
Total heat supply3)	34	35	43	50	85	106
- Fossil fuels	15	15	16	5	1	0
- Biomass	19	19	24	35	53	46
- Solar collectors	0	0	0	2	8	15
- Geothermal	0	0	0	1	3	5
- Heat pumps 2)	0	0	1	3	10	21
- Electric direct heating	0	1	1	3	10	18
- Hydrogen	0	0	0	0	0	0
RES share (including RES electricity)	56%	57%	62%	91%	99%	100%
electricity consumption heat pumps (TWh/a)	0.0	0.0	0.3	0.7	1.4	3.1

Installed Capacity [GW]	2012	2015	2020	2030	2040	2050
Total generation	3	3	3	5	10	20
- Fossil	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas (w/o H2)	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
- Diesel	0	0	0	0	0	0
- Nuclear	0	0	0	0	0	0
- Hydrogen (fuel cells, gas power plants	0	0	0	0	0	0
- Renewables	2	3	3	5	10	20
- Hydro	2	2	2	2	2	2
- Wind	0	0	1	2	3	4
of which wind offshore	0	0	0	0	0	0
- PV	0	0	0	1	5	13
- Biomass (& renewable waste)	0	0	0	0	0	1
- Geothermal	0	0	0	0	0	0
- Solar thermal power plants	0	0	0	0	0	0
- Ocean energy	0	0	0	0	0	0
Variable RES (PV, Wind, Ocean)	0	0	1	2	7	17
Share of variable RES	10%	18%	23%	46%	71%	84%
RES share (domestic generation)	87%	98%	98%	100%	100%	100%

Final Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total (incl. non-energy use)	144	156	176	192	231	244
Total energy use 1)	142	153	174	190	229	242
Transport	66	74	82	88	83	72
- Oil products	66	74	82	75	48	0
- Natural gas/biogas	0	0	0	0	1	0
- Biofuels	0	0	0	6	11	16
- Synfuels	0	0	0	0	0	0
- Electricity	0	0	1	7	24	56
RES electricity	0	0	1	7	24	56
- Hydrogen	0	0	0	0	0	0
RES share Transport	0%	0%	1%	15%	42%	100%
Industry	36	38	44	50	60	72
- Electricity	7	7	8	11	16	25
RES electricity	6	7	8	11	16	25
- Public district heat	0	1	0	0	0	0
RES district heat	0	1	0	0	0	0
- Hard coal & lignite	1	1	0	0	0	0
- Oil products	10	9	11	2	0	0
- Gas	1	1	1	1	0	0
- Solar	0	0	0	1	2	6
- Biomass	17	19	23	33	37	33
- Geothermal	0	0	1	2	4	8
- Hydrogen	0	0	0	0	0	0
RES share Industry	66%	70%	72%	93%	99%	100%
Other Sectors	40	40	47	52	86	99
- Electricity	26	27	31	34	44	57
RES electricity	24	27	31	34	44	57
- Public district heat	0	0	0	0	0	0
RES district heat	0	0	0	0	0	0
- Hard coal & lignite	0	0	0	0	0	0
- Oil products	6	7	8	2	1	0
- Gas	0	0	0	0	0	0
- Solar	0	0	0	1	6	10
- Biomass	8	6	7	12	29	20
- Geothermal	0	0	0	2	7	13
- Hydrogen	0	0	0	0	0	0
RES share Other Sectors	79%	82%	82%	95%	99%	100%
Total RES	55	60	71	109	179	242
RES share	39%	39%	41%	57%	78%	100%
Non energy use	2	3	3	2	2	2
- Oil	2	3	3	2	2	2
- Gas	0	0	0	0	0	0
- Coal	0	0	0	0	0	0

Energy-Releated CO2 Emissions [Million tons/a]	2012	2015	2020	2030	2040	2050
Condensation power plants	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil + Diesel	1	0	0	0	0	0
Combined heat and power plants	0	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil	0	0	0	0	0	0
CO2 emissions power and CHP plants	1	0	0	0	0	0
- Hard coal (& non-renewable waste)	0	0	0	0	0	0
- Lignite	0	0	0	0	0	0
- Gas	0	0	0	0	0	0
- Oil & diesel	1	0	0	0	0	0
CO2 intensity (g/kWh)	0	0	0	0	0	0
without credit for CHP heat	0	0	0	0	0	0
- CO2 intensity fossil electr. generation	760	760	844	287	1,519	1,493
- CO2 intensity total electr. generation	760	760	844	287	1,519	1,493
CO2 emissions by sector	7	8	9	6.7	4	0
- % of 1990 emissions (Mill t)	53%	54%	62%	48%	29%	0%
- Industry 1)	1	1	1	0	0	0
- Other sectors 1)	0	1	1	0	0	0
- Transport	5	6	6	6	4	0
- Power generation 2)	1	0	0	0	0	0
- Other conversion 3)	0	1	1	1	0	0
Population (Mill.)	5	5	5	5	6	6
CO2 emissions per capita (t/capita)	2	2	2	1	1	0

Primary Energy Demand [PJ/a]	2012	2015	2020	2030	2040	2050
Total	177	184	228	242	297	325
- Fossil	96	98	115	90	55	3
- Hard coal (& non-renewable waste)	3	3	0	0	0	0
- Lignite	0	0	0	0	0	0
- Natural gas	0	0	2	3	2	0
- Crude oil	93	95	113	87	53	2
- Nuclear	0	0	0	0	0	0
- Renewables	81	86	112	152	242	322
- Hydro	26	29	32	33	33	33
- Wind	2	4	7	15	26	42
- Solar	0	0	0	6	31	75
- Biomass (& renewable waste)	28	28	34	61	100	104
- Geothermal	25	25	40	37	53	68
- Ocean energy	0	0	0	0	0	0
- of which non-energy use	2	3	3	2	2	2
Total RES	81	86	112	152	242	322
RES share	46%	47%	49%	63%	81%	99%

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