URBAN ENERGY TRANSITION FOR THE GREATER METROPOLITAN AREA OF THE CENTRAL VALLEY OF COSTA RICA

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ABBREVIATIONS

ARESEP	Public Services Regulatory Authority
BAU	Business-as-usual
BCCR	Central Bank of Costa Rica
CHP	Combined heat and power
CNFL	National Company of Light and Power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
GDP	Gross domestic product
GIS	Geographic information system
GW	Gigawatt
GWh	Gigawatt hour
ICE	Costa Rican Electricity Institute
INEC	National Institute of Statistics and Census
IRENA	International Renewable Energy Agency
km^2	Square kilometre
kW	Kilowatt
kWh	Kilowatt hour
LPG	Liquefied petroleum gas
MINAE	Ministry of Environment and Energy
MIVAH	Ministry of Housing and Human Settlements
MSW	Municipal solid waste
Mt	Megatonne
MW	Megawatt
NDC	Nationally Determined Contribution
NDP	National Decarbonisation Plan
NZC	Net zero carbon
PV	Photovoltaic
SEPSE	Planning Secretariat of the Energy Subsector
USD	United States dollar

EXECUTIVE SUMMARY

As with other countries in Latin America and the Caribbean, Costa Rica is highly vulnerable to the effects of climate change, even though it contributed less than 0.05% of global greenhouse gas emissions in 2019. The country has developed national vision of transforming its economy to net zero emissions by 2050 and an ambitious decarbonisation plan with sectoral break-downs including for the transport and buildings sectors. To meet Costa Rica's decarbonisation target, there is a need for the national government as well as local municipalities to step up their actions. This is because that scaling up the use of clean energy and improving energy efficiency at both the national and local levels are key in realising the shared decarbonisation objective. This would particularly require support from local governments in implementation when it involves urban planning interplaying with energy use at the local levels. Over the past years, municipalities have been undertaking efforts to improve the sustainability of their jurisdictions, to which decarbonisation actions are well in aligned with this endeavor.

Despite that Costa Rica's central government is in charge of developing national energy and transport policies and regulations, there is large technical potential for decarbonisation in cities, given that 75% of the country's population lives in urban areas. This report explores plausible technological options in the Greater Metropolitan Area of the Central Valley of Costa Rica to contribute towards achieving the national decarbonisation goal.

IRENA's urban planning tool was implemented to assess technological pathways that enable the decarbonisation of cities. The analysis focused on cities within the Greater Metropolitan Area of Costa Rica, analysing in detail five representative districts. Two technological pathways – considering the existing policy measures in the country – were evaluated for each district, and the respective results were compared against a business-as-usual (BAU) scenario in which no climate or energy-related policies are in place.

The first pathway, the National Decarbonisation Plan (NDP) scenario, scales the targets set in the country's National Decarbonisation Plan down to the city level, achieving a significant reduction in emissions while increasing the penetration of renewable energy sources and the electrification of economic activities in the transport, industry, residential and commercial sectors. The second pathway, the net zero carbon (NZC) scenario, reaches the maximum level of decarbonisation by electrifying all activities to reach a full reduction of carbon emissions in the energy and transport sectors by mid-century – an ambitious target that is useful for exploring benefits and costs.

The analysis shows that reducing emissions in cities by around 90% by 2050 compared to BAU is technically possible in the NDP scenario. Crucially, the results demonstrate that it is still possible to reach a 100% emission reduction in this same period in the NZC scenario. In other words, there are no technological barriers to meeting high-ambition targets by 2050.

Decarbonising cities not only brings reductions in emissions but also results in savings of energy costs to cities and their inhabitants. These savings are related primarily to lower operational costs linked to renewable energy technologies and energy efficiency improvements. To meet the NZC scenario, a mix of technologies needs to be deployed, including: solar photovoltaic (PV) systems, energy storage systems, air-source heat pumps, and electro-mobility for private, public and freight fleets. The results suggest that this scenario requires higher total costs, including for integrating these technologies, along with grid infrastructure upgrades necessitated by increased electricity demand from electric vehicles.

Results extrapolated to the concession area of the state power utility CNFL highlight that the overall costs for cities in all scenarios are similar. While the decarbonisation of most cities will bring energy cost savings of up to 18% compared to the BAU scenario by 2050, cities with low population density, large geographic area and low solar PV production may experience relatively higher costs. More importantly, the analysis shows that investments in the NDP and NZC scenarios are mainly in zero-emission technologies, thereby reducing emissions and leading to co-benefits associated with health. The adoption of public transport promoted in these two decarbonisation scenarios also brings co-benefits from reduced congestion and accidents.

This study recommends key actions needed in cities to enable the transformational change towards decarbonisation. City energy-related goals should focus on reducing carbon emissions (particularly from transport), improving energy efficiency across sectors, increasing renewable energy integration, and increasing cycling and walking as alternative mobility options. To enable this transformation, however, decision makers will have to consider in their urban planning the need to overcome key challenges, including institutional barriers, technical aspects, fiscal concerns, tariffs, employment and uncertainty. Among other measures, cities in Costa Rica can adopt good practices, enforcement of standards, long-term vision, the use of advanced planning tools, involvement in national planning, and circular economy activities to maximise the benefits of decarbonising their energy and transport sectors.

1

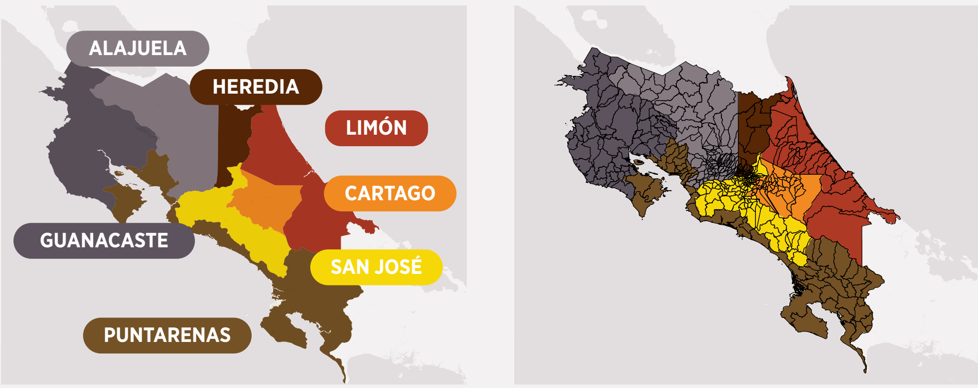
INTRODUCTION

To address the global climate challenge, Costa Rica has committed to fully decarbonising its economy by 2050 and has developed a corresponding plan to achieve this target (UNFCCC, 2019; UNFCCC, 2018). As in many countries, implementing such a comprehensive plan would require efforts at all levels. Although Costa Rica's central government is in charge of developing national energy and transport policies and regulations (Presidencia de La República, 2019), there is large potential for decarbonisation in cities, given that 75% of the country's population lives in urban areas. This report explores plausible technological options in the Greater Metropolitan Area of the Central Valley of Costa Rica to contribute towards achieving the national decarbonisation goal.

1.1 National context

Costa Rica has a population of around 5 million inhabitants within a total area of 51 060 square kilometres (km^2), making it the third densest country in the Central America region (following El Salvador and Guatemala) with 98 inhabitants per km^2. The territory is structured in 7 provinces, 82 cantons (municipalities) and 482 districts (Figure 1). The rapidly growing Greater Metropolitan Area, which includes the capital, San José, and the provinces of Alajuela, Heredia and Cartago, is home to 2.2 million inhabitants, nearly half of the population, distributed within an area of 2 044 km^2.

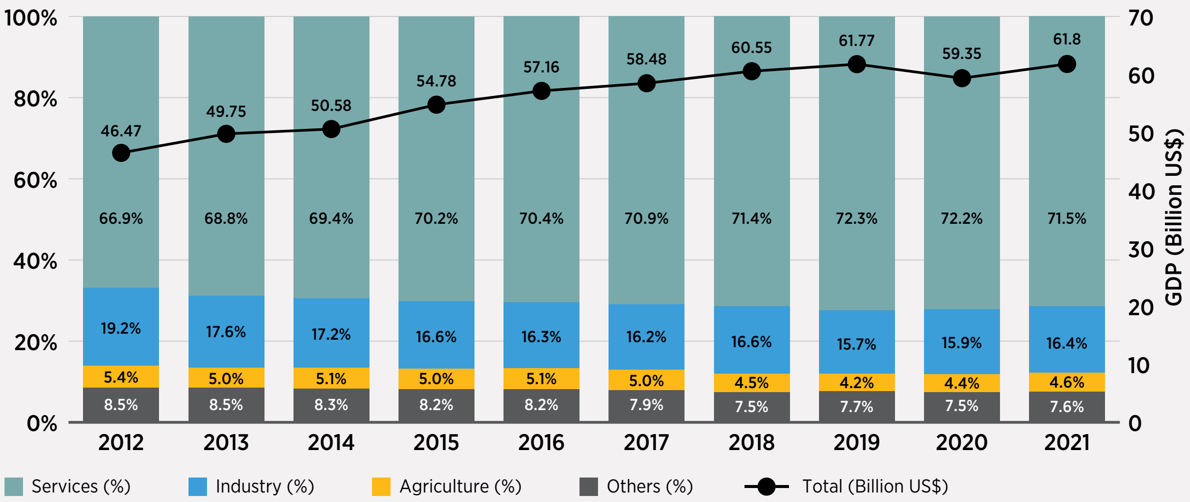
FIGURE 1: Map of Costa Rica by province, municipality and district



Source: IRENA, 2021a; Guías Costa Rica, n.d.

Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

FIGURE 2: Costa Rica's GDP by sector, 2012 to 2021



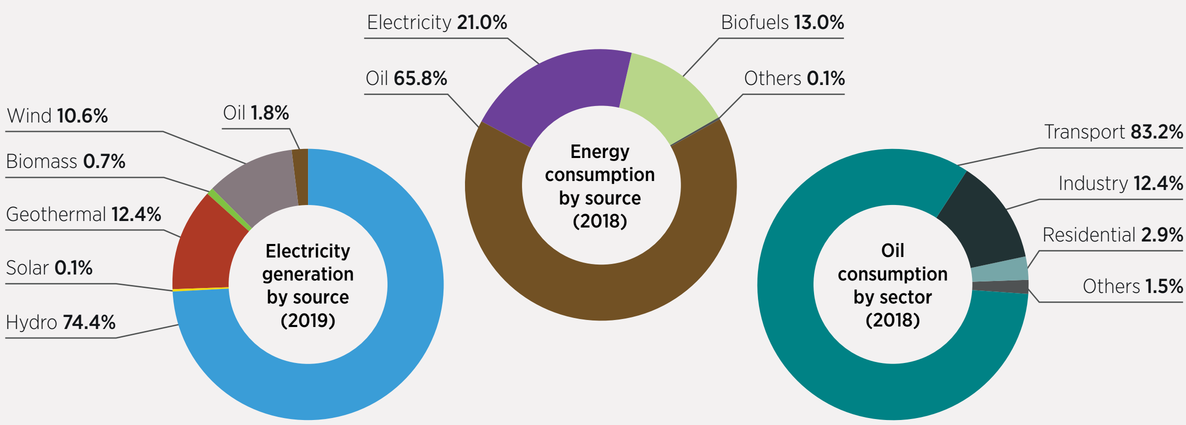
Note: The year 2012 is taken as the base year referenced for GDP.

Source: Based on data from Central Bank of Costa Rica, 2020a and on projections from World Bank, 2020.

Economic growth in Costa Rica has depended heavily on the services and industry sectors (Figure 2), which have largely driven the more than 30% increase in the country's gross domestic product (GDP) between 2012 and 2019 (Central Bank of Costa Rica, 2020a; IMF, 2020). The economy has been fuelled primarily by clean electricity generated from renewable energy sources such as hydropower, geothermal and wind energy, and by petroleum-based fuels used mainly for transport and industry (Figures 3).

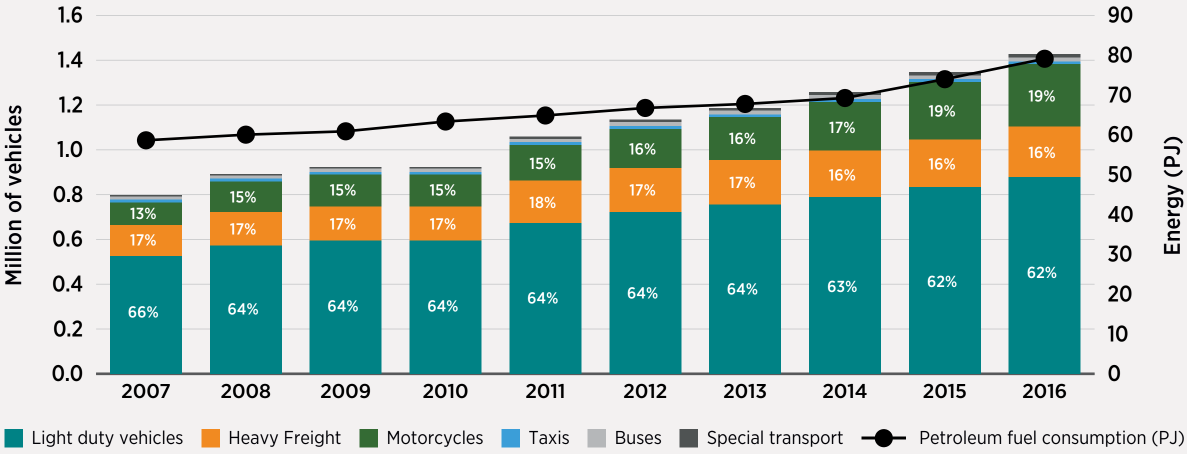
As shown in Figure 3(c), the transport sector is the largest consumer of oil, at 83% in 2018, followed distantly by the industry (12%) and residential (3%) sectors. Consumption of petroleum-based transport fuels has increased over the last 13 years alongside the growth in internal combustion engine vehicles, assuming similar driving behaviours and fuel economy since 2007 (Figure 4) (SEPSE and MINAE, 2018).

FIGURE 3: (a) Electricity generation by source (2019), (b) Energy consumption by source (2018), (c) Oil consumption by sector (2018)



Source: ICE, 2019; MINAE, 2019a.

FIGURE 4: Number of vehicles and fossil fuel consumption by transport mode, 2007 to 2016

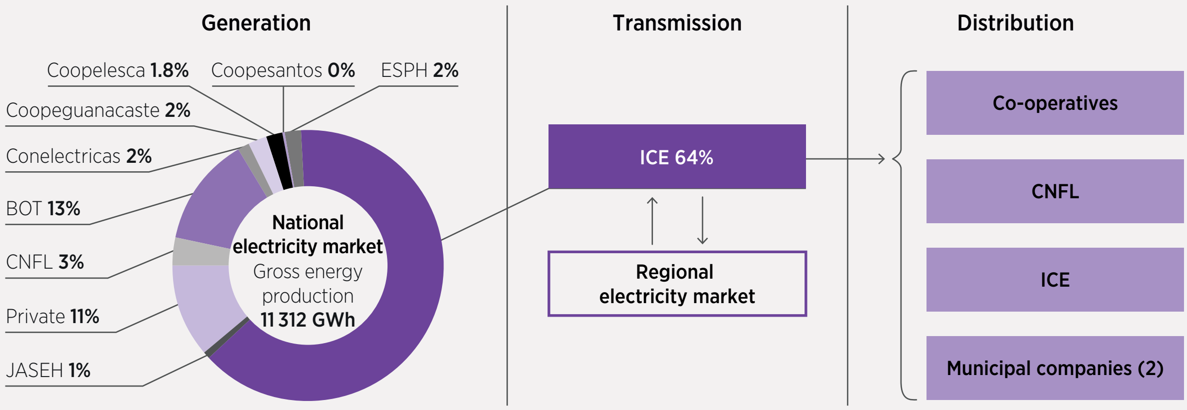


Source: Based on publicly available information and on energy consumption data from MINAE (2018) and fleet composition data from SEPSE (n.d.).

Among the nine power suppliers, the state-run ICE (Instituto Costarricense de Electricidad, or Costa Rican Institute of Electricity) accounts for the bulk of the electricity supply. It provides 63.7% of the total installed generation capacity of 3 500 megawatts (MW) and also monopolises the national transmission market (Figure 5). Two municipally owned energy utilities, ESPH and JASEC, operate only 3% of the national total generation capacity, while co-operatives account for around 5.9%.

Meanwhile, privately owned energy companies account for 24% of the capacity, with a breakdown of 11.10% (Law No. 7 200 Cap 1) and BOT (Build-Operate-Transfer) 12.96% (Law No. 7 200 Cap 2), which is below the 15% cap capacity stipulated by law. Generation companies cannot engage in the direct sale of electricity. However, private co-operatives can sell the electricity that they generate to one another (Law No. 8 345, art. 9) and to the transmission grid operator (ICE), which is one of four concessionary energy providers at the distribution level.

FIGURE 5: Structure of the power sector in Costa Rica in 2019



Note: Institutionally, within the electricity sector, MINAE is responsible for policy, ARESEP for regulation and ICE for system operation and planning.

Based on: Data from ICE (2019).

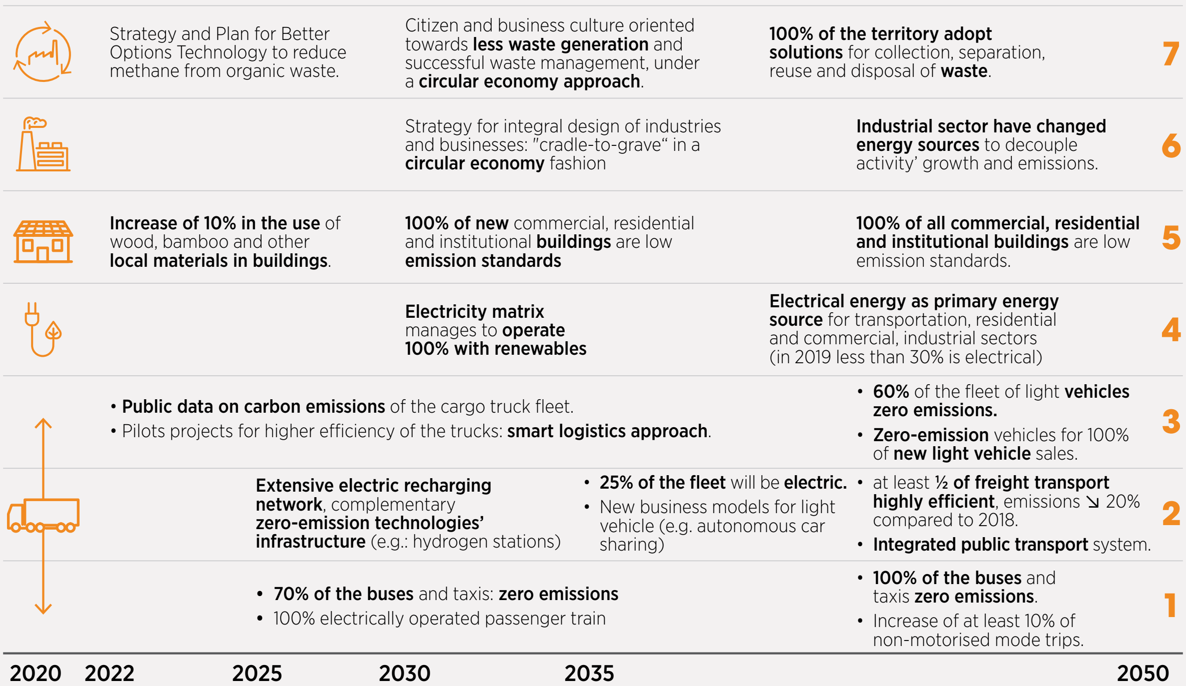
1.2 National Decarbonisation Plan and the role of cities

Even though Costa Rica contributed less than 0.05% of global greenhouse gas emissions in 2019, like other countries in Latin America and the Caribbean it is highly vulnerable to the effects of climate change. Consequently, different policy actions have been implemented over the past decade to reinforce the country's engagement with global targets. These actions and intentions are manifested in Costa Rica's Nationally Determined Contribution (NDC) towards reducing emissions under the Paris Agreement, which calls for a 44% reduction in the country's greenhouse gas emissions by 2030 and represents one of the most ambitious targets in the region (CEPAL, 2018).

Cities in Costa Rica are directly involved in climate change mitigation through the Cantonal Country Programme, driving change and assuming multiple roles including decision making, planning, managing assets and operating local energy suppliers, among others. In this context, municipalities are also key actors in the transition towards 2050, in which new energy technologies in the transport, industry and residential sectors will be deployed under the guidance of the national government.

In 2019, Costa Rica launched a National Decarbonisation Plan (NDP) as an action to combat climate change (Government of Costa Rica and MINAE, 2019a; UNFCCC *et al.*, 2020). The NDP presents a decarbonisation pathway towards net zero emissions by 2050. It includes seven lines of action focused specifically on the contribution from cities, as summarised below and illustrated in Figure 6. Implementing the NDP therefore requires collective efforts involving all relevant stakeholders.

FIGURE 6: Lines of action in Costa Rica's National Decarbonisation Plan, with implications for cities



Source: Based on data from Government of Costa Rica and MINAE, 2019b.

- Line of action 1: developing a mobility system based on safe, efficient, and sustainable public transport and active mobility schemes.

- Line of action 2: transforming the light-duty vehicle fleet to zero emissions, boosted by renewable energy.

- Line of action 3: promoting a freight transport sector that adopts modalities, technologies and energy sources towards achieving zero emissions or the lowest emissions possible.

- Line of action 4: updating the electricity system – covering capacity, flexibility and intelligence – and scaling up the renewable energy supply at a competitive cost that may be supported by cost-effective investment programmes to ensure affordability for final energy consumers.

- Line of action 5: developing buildings of different uses (commercial, residential, institutional) based on high efficiency standards and low-emission processes.

- Line of action 6: transforming the industry sector through processes and technologies that use renewable energy sources and are sustainable and efficient, with low or zero emissions.

- Line of action 7: embracing the principle of a circular economy, designed to promote the development of an integrated system with maximum efficiency, low greenhouse gas emissions and waste management.

1.3 Methodology and approach

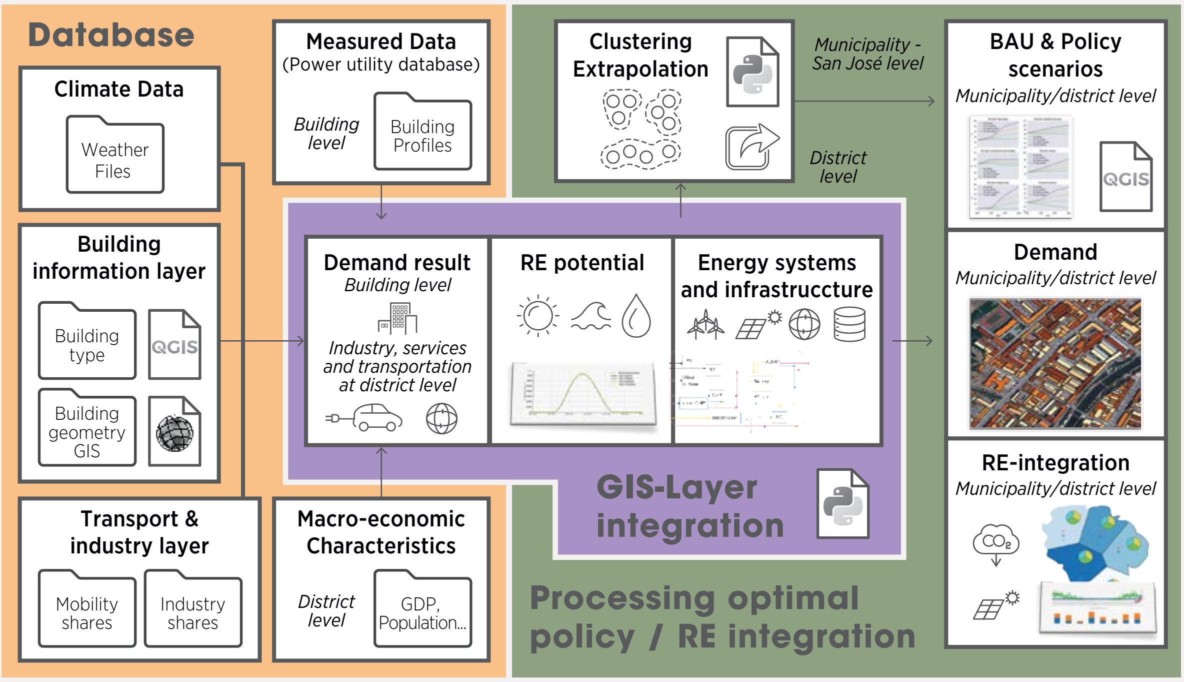
This report aims to improve understanding of the decarbonisation pathways for municipalities in Costa Rica, with a focus on five representative districts located within the concession area of the state-owned power utility CNFL (Compañía Nacional de Fuerza y Luz, or National Company of Power and Light).

The collected data were embedded in a geographic information system (GIS) database that details the features needed to characterise the districts from an energy planning perspective. In-depth analyses were then executed for these districts, and the respective results were extrapolated to the utility scale, with the aim of supporting decision makers at the local and national levels. For data that were not accessible, advanced data mining techniques were employed to identify typical districts based on demographic, socio-economic and energy-related data collected at the national, municipal, district and household levels (see the next section).

The overall methodology for the analysis is shown in Figure 7. The approach comprises a combination of data mining and optimisation techniques to generate data-driven knowledge to better estimate the potential for integrating renewable energy in the urban context of Costa Rica. These techniques include:

- **Data collection:** An exhaustive data collection process at the district or municipal scale was executed to implement an advanced classification process facilitating quantification of the potential for renewable energy integration by district, based on the main drivers and characteristics of districts.

FIGURE 7: Overview of the methodology developed for the assessment of urban renewable energy integration



Note: RE = renewable energy.

- **GIS-embedded database:** Based on the data collected, a GIS-embedded database was produced to support districts/municipalities in deploying detailed urban energy planning based on local geospatial constraints and renewable energy integration potential.

- **Clustering and identification of representative districts:** A clustering technique was then applied to identify five representative districts that are used to study the decarbonisation process of cities. District-level results were extrapolated to the power utility's concession area to provide insights for planning the electricity infrastructure.

- **District-level database:** The database produced was adjusted to each of the five representative districts. Each district was characterised by its GDP, population growth and energy consumption by type of customer (residential, industrial, commercial, transport, etc.). Energy consumption was disaggregated into end uses to study the different technologies available for decarbonisation of the district. Information related to renewable energy technologies (*e.g.* rooftop solar PV, horizontal wind turbines) and energy storage systems (*e.g.* batteries, hydrogen) was identified to produce a database of low-carbon technologies that can contribute to decarbonising the energy sectors of these districts.

- **Urban planning scenarios:** Three scenarios were produced, and the benefits and costs of each scenario were compared to understand the potential of renewable energy in each district:

  - *BAU scenario*: This is the business-as-usual (BAU) scenario that exists in the absence of decarbonisation strategies. It assumes that industries consume energy in a similar manner as currently and that the transport sector continues to use fossil fuels in a similar distribution.

- *NDP scenario*: This scenario scales the actions of the National Decarbonisation Plan (NDP) down to cities by promoting efficiency, a switch to renewable energy technologies and the electrification of energy end uses.

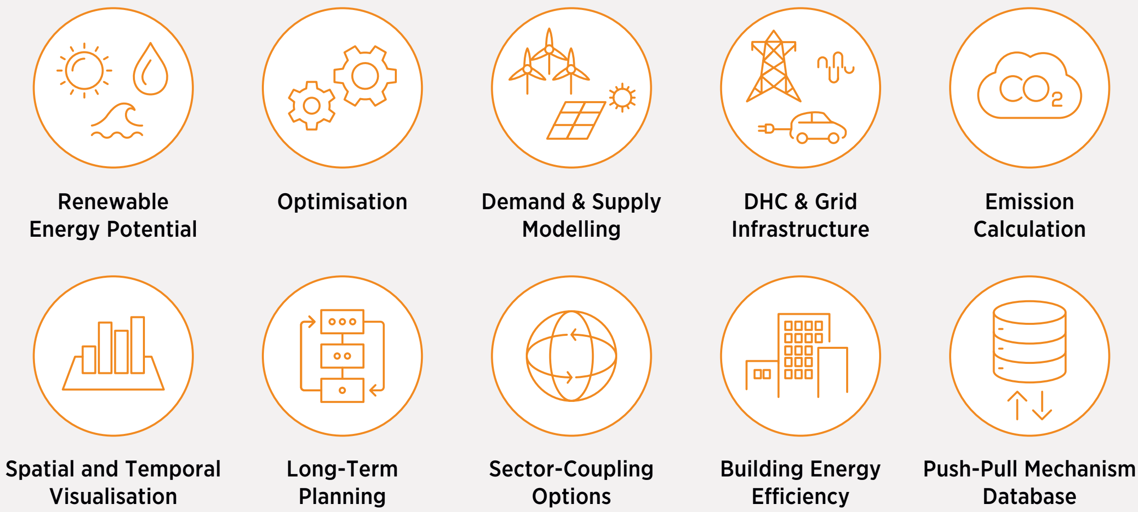
- *NZC scenario*: This scenario aims at net zero carbon emissions by 2050 by enforcing the actions mentioned for the NDP scenario. Costa Rica's current Nationally Determined Contribution (NDC) is already compatible with this scenario.

- **Optimisations and simulations using IRENA's Planning Platform for Urban Renewable Energy:** The planning tool developed by the International Renewable Energy Agency (IRENA) was applied within each representative district, considering the database and locally available technologies to estimate the costs and environmental impacts of each scenario.

The tool aims to support the decision-making process for long-term urban energy planning in cities by analysing and optimising the technical and financial viability of integrating renewable energy technologies. Considering the renewable energy resource potential and combining spatial analysis and energy systems modelling across different sectors, the tool compares different solutions with the objective of minimising carbon dioxide (CO_2) emissions from the energy sector and buildings, as well as the total energy system costs. The main features of the tool are illustrated in Figure 8.

FIGURE 8: IRENA Planning Platform for Urban Renewable Energy features at a glance

The IRENA Planning Platform for Urban Renewable Energy aims at offering a wide range of applications for urban renewable energy integration and optimisation, network design, mapping and visualisation.



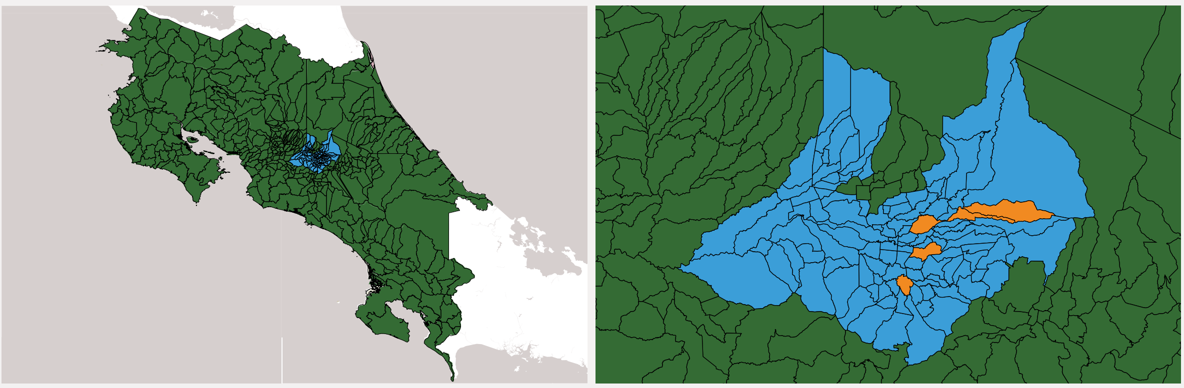
2

THE URBAN ENERGY CONTEXT AND REPRESENTATIVE DISTRICTS OF THE GREATER METROPOLITAN AREA

2.1 Characterisation of districts in the Greater Metropolitan Area

The state-owned power company CNFL supplies electricity in most districts of the Greater Metropolitan Area, as shown in light blue in Figure 9. To characterise these districts in the analysis, multiple sources of information were collected, combined and represented in GIS

FIGURE 9: Map of CNFL coverage (in light blue) showing districts of Costa Rica (left) and the zoomed-in coverage area provided by MIVAH for the study (right)



Note: The five districts analysed in detail in the report are highlighted in yellow on the MIVAH[1] map (right).
Disclaimer: Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

1. The map (right) was provided by MIVAH (Ministry of Housing and Human Settlements) in the report review process.

format. The resulting database comprises key features including the surface area, population density, economic growth, energy consumption, and number and type of customer (residential, commercial or industrial), among others. For example, high-resolution data were gathered on monthly energy consumption for each building within the districts and were used to produce time-series demand profiles. In addition, the end uses for each technological carrier at a building level were identified based on energy surveys.

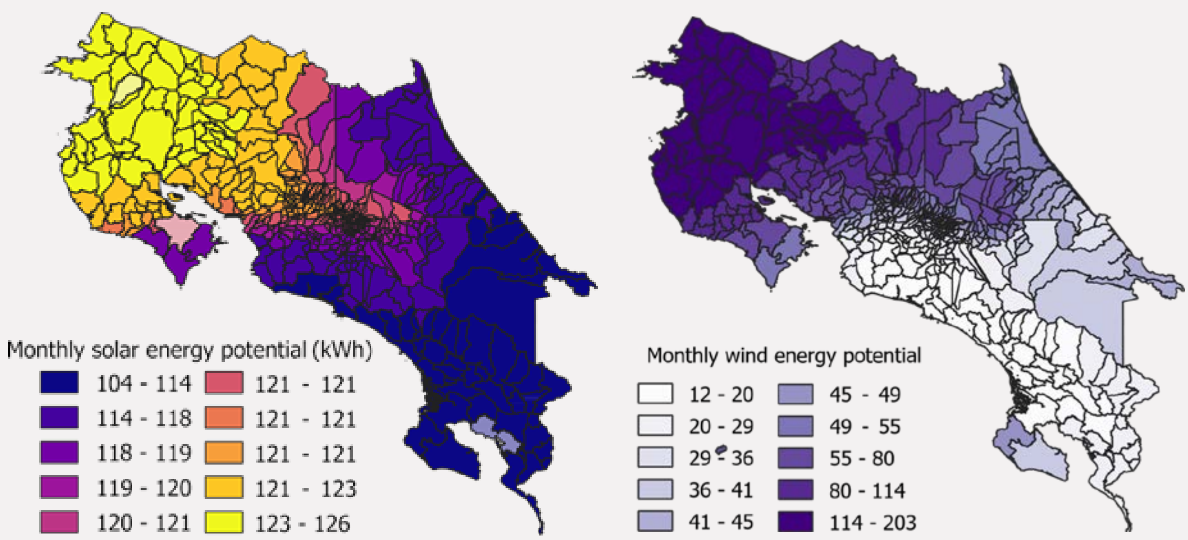
2.2 Local renewable energy options

Costa Rica is known for its vast natural resources, which greatly increase the country's potential for deploying renewable energy technologies. This study specifically explores the potential of solar and wind energy resources in districts, with the greatest values found in the northwest (Figure 10).

In terms of technology applications in the built environment, solar PV systems have increasingly gained attention due largely to two attributes: 1) the installations can be modular, while the system efficiency is not impacted significantly by the scale of installed capacity; and 2) the levelised cost of electricity at the utility scale has declined substantially in the past decade and is expected to continue to drop in the coming years, making solar PV generation cost-competitive with fossil fuel-based power generation in a growing number of regions and contexts including urban settings (IRENA, 2021b; IRENA, 2020a).

Wind turbines, unlike solar PV, are currently less applicable within urban areas and are increasingly seen in the surrounding areas of cities as part of distributed energy generation located close to the load. Although urban wind turbine technologies have been progressing, they are still relatively rare despite pilot projects.

FIGURE 10: Average monthly renewable energy potential per square metre by district in 2018 for (a) solar energy and (b) wind energy at 10 metres above surface level



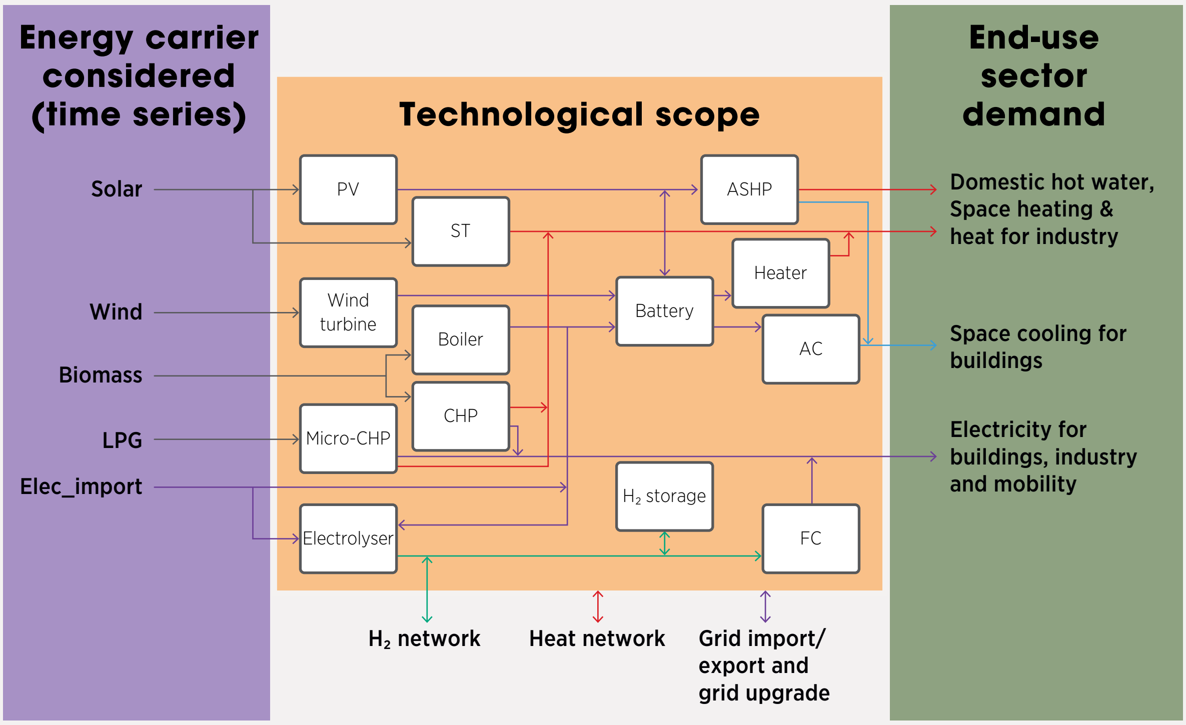
Biomass resources such as sugar cane, coffee, pineapple and oil palm, as well as biomass from animal farms and municipal waste, also offer an opportunity for local renewables, provided that the radius of collection is cost-effective economically. On most occasions, biomass-based energy applications bring multiple benefits including social, economic and environmental benefits for local residents.

The analysis considers a suite of technologies that can contribute to the decarbonisation of districts (Figure 11). To assess the role of storage technologies within Costa Rica's urban context, flow redox batteries and hydrogen were included in the technology database, along with lithium-ion batteries. Fuel cell and electrolyser technologies have significant potential as the government has supported their further exploration, in addition to the ongoing effort to produce hydrogen using the country's existing renewable sources.

Table 1 provides an overview of key technologies facilitating the integration of renewable energy included in the scenarios.

The energy network plays a critical role in accommodating local renewables. At present, utility companies supply electricity to the concession areas through a radial distribution network. However, from a technical perspective, cities could also inject electricity from distributed energy generation into the power grid, making the transition from passive to active distribution networks (meshed distribution networks)[2]. To enable this, network reinforcements might be required to cope with the integration of renewable energy technologies.

FIGURE 11: Technologies included in the scope of this study



2. The study has also recognised the regulatory challenges in the country, which are beyond the scope of this study.

TABLE 1: Overview of key technologies facilitating the integration of renewable energy included in the scenarios

TECHNOLOGY	CARRIERS	DEMAND	EFFICIENCY	LIFETIME (YEARS)
Network				
Grid	electricity import	electricity	0.99	50
Grid upgrade	electricity import	electricity	0.99	50
Energy converter				
Air conditioner (grid)	electricity	cooling	0.86	20-30
Heat (grid)	electricity	heat	0.8	20-30
Air-source heat pump – heating mode	electricity	heat	3.2	20
Air-source heat pump – cooling mode	electricity	cooling	4.5	20
Rooftop solar PV	solar	electricity	0.14	30
Solar thermal – evacuated tube solar collectors	solar	heat	0.46	15
Horizontal-axis wind turbine – onshore	wind	electricity	–	20
Micro combined heat and power – heating mode	LPG	electricity; heat	0.3; 0.519	12
Micro combined heat and power – cooling mode	LPG	electricity; cooling	0.3; 0.615	12
Heat pump chiller	electricity	cooling	2.6	20
Waste boiler	MSW	electricity	0.34	15
Electrolyser (hydrogen generator)	electricity	hydrogen	0.8	20
Fuel cell	hydrogen	electricity	0.7	20
Energy storage				
Lead-acid battery	electricity	electricity	0.75-0.85	5-15
Lithium-ion battery	electricity	electricity	0.75-0.9	10-20
Flow redox battery	electricity	electricity	0.70-0.75	10-20
Hydrogen storage	hydrogen	hydrogen	0.62-0.82	10-30

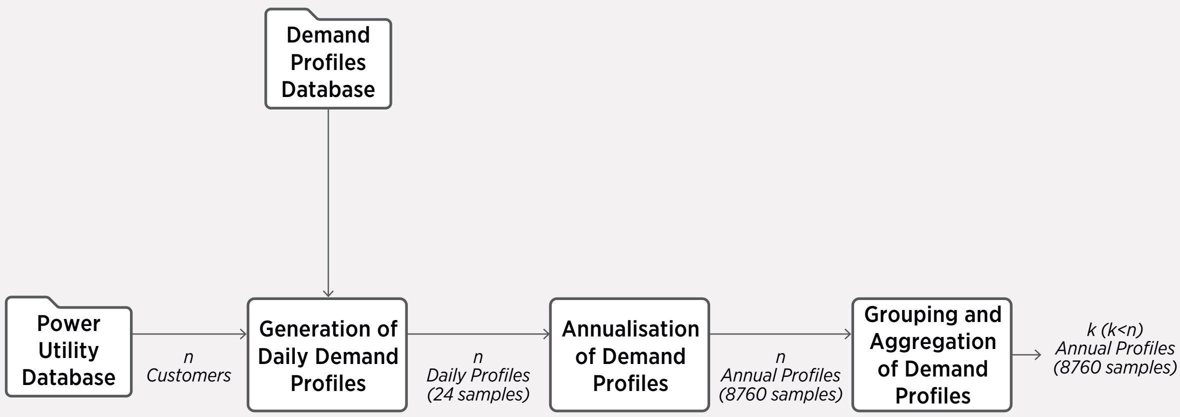
To account for these upgrades, the analysis considered the costs of upgrading the current network and increasing its capacity to host more renewable energy technologies in the shift towards the decarbonisation of cities. Further analysis can be performed to assess factors such as contingency, voltage drop, and short-circuit fault or line outages, by exporting the results to network simulation tools for in-depth evaluation of the technical challenges and benefits of implementing distributed solutions.

2.3 Energy demand

Time-series load profiles per customer within each district were computed to estimate their energy demand at an hourly basis for one year, as shown in Figure 12. Because Costa Rica is located in a tropical climate zone with an average year-round temperature of 25 degrees Celsius (°C), domestic space heating or cooling systems are not commonly found. However, districts located near the coast may require assessing cooling demand in the future. In the Greater Metropolitan Area, the use of cooling technologies is limited to commercial, industry and public buildings. The energy required for domestic hot water (or eventually cooling) is produced mostly using electricity-based systems. These end uses are represented in the electricity profiles.

This power utility database includes all the geo-referenced customers of the electricity company, classified by sector (residential, commercial or industrial) with the average monthly energy consumption in kilowatt-hours (kWh).

FIGURE 12: Methodology to produce time-series load profiles of buildings



Demand profiles database

This database considers high-resolution measured data on the load profile (10 minutes) from 1351 customers. These data have been cleaned of potential measurement errors or outages and then classified into weekday and weekend. The final classification of the load profiles is detailed in Table 2, based on the sectoral categories defined in Table 3.

TABLE 2: Details on the amounts of available monitored profiles

SECTOR	NUMBER OF PROFILES	WEEKDAY	WEEKEND
Commercial	137	99	38
Residential	1145	831	314
Industrial		69	

TABLE 3: Defined customer categories by monthly average electricity consumption

<table>
<tr><th>RESIDENTIAL</th><th>COMMERCIAL</th><th>INDUSTRIAL</th></tr>
<tr><td>0 – 100</td><td rowspan="3">0 – 300</td><td rowspan="7">0 – 10 000</td></tr>
<tr><td>100 – 200</td></tr>
<tr><td>200 – 300</td></tr>
<tr><td>300 – 500</td><td rowspan="3">300 – 1 000</td></tr>
<tr><td>500 – 700</td></tr>
<tr><td rowspan="4">700+</td></tr>
<tr><td rowspan="3">1 000+</td></tr>
<tr><td>10 000 – 100 000</td></tr>
<tr><td>100 000+</td></tr>
</table>

Generation of daily demand profiles

Daily load profiles for each geo-referenced customer not included in the demand profiles database were generated using the procedure suggested in Leiva *et al*. (2017). In this procedure, the average monthly electricity consumption of each customer from the power utility database is classified according to its sector in Table 3, then daily profiles are generated with a Gaussian distribution fitted to the demand profiles database of the reference sector. The distribution of customers and electricity consumption is presented in Table 4.

TABLE 4: Customer information and electricity consumption of the five representative districts in 2018

DISTRICT	DESAMPARADOS	SAN VICENTE	SAN PEDRO	SAN ISIDRO	SAN RAFAEL
Total customers	11 746	12 556	13 258	6 261	2 296
Residential customers	10 378	11 063	10 590	5 536	1 996
Commercial customers	1 323	1 455	2 613	691	175
Industrial customers	45	38	55	34	125
Total yearly electricity consumption (GWh)	49.24	65.80	107.19	26.95	8.21
Yearly residential electricity consumption (GWh)	27.71	35.08	32.46	17.18	6.41
Yearly commercial electricity consumption (GWh)	19.63	25.42	55.49	8.07	1.48
Yearly industrial electricity consumption (GWh)	1.90	5.29	19.24	1.70	0.31

Note: GWh = gigawatt-hours.

Source: Data processed in the context of the analysis from the utility-level database.

2.4 Estimation of roof areas in buildings

To better quantify the potential area of rooftop available to install solar PV systems, the building area was included in the analysis. Although GIS databases were available for some municipalities, the data were insufficient to approximate the rooftop area of each building. Therefore, surveys at the national level undertaken by the National Institute of Statistics and Censuses (INEC) were retrieved. According to the National Household Survey of 2019 (INEC, 2019), the floor area was reported for a portion of houses in every region of the country.

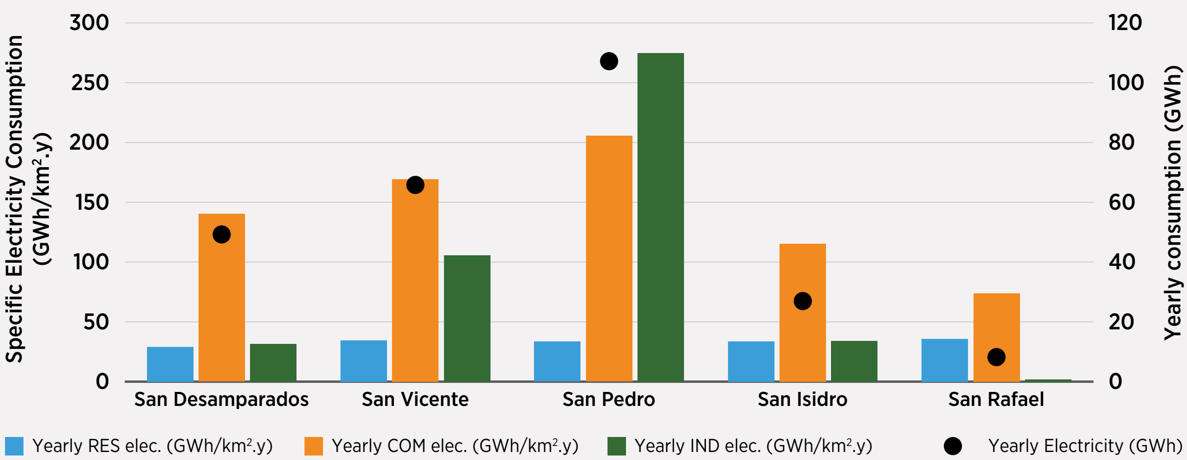
With this information and data from the Central Region of the country (around 970 000 buildings), the average area of the residences was determined. Information published by INEC on the construction sector between 2015 and 2017 made it possible to estimate the area of buildings in the commercial and industrial sectors (INEC, 2018).

2.5 Creation of representative districts

By applying data-mining techniques and considering demographic and geographic characteristics along with energy use, customer type, and renewable energy potential, five districts were identified to represent the 109 districts of the CNFL concession area. The five districts are described briefly below, and Figure 13 characterises them according to their electricity needs.

- **District 1 – Desamparados de Desamparados:** This is the densest district in the country with more than 35 000 inhabitants, and also has a low Cantonal Human Development Index in Costa Rica. While the district's energy consumption is not the highest in the Greater Metropolitan Area, it is expected to double by 2050 driven by economic growth, even if population growth has slowed. Of the nearly 12 000 electricity customers in this district, 88% are residential, 11% are commercial, and only 1% are industrial. The potential for deploying solar PV systems in the district at a building level has been investigated in previous works (Valverde *et al.*, 2015), finding low penetration due mainly to the technology cost. However,

FIGURE 13: Electricity consumption by end-use sector and electricity demand for each representative district in 2018



Note: GWh = gigawatt-hour.

the cost is constantly decreasing because of economies of scale, and incentives for solar PV deployment in the medium and long terms will likely be available to enhance adoption. Due to the district's density and number of customers, it will likely face infrastructure planning challenges for technologies that require a large area for deployment.

- **District 2 – San Vicente de Moravia:** This district of 30 000 inhabitants has experienced rising energy needs in recent years, driven primarily by economic growth. Of the more than 12 500 electricity customers in the district, 88% are residential, 11.5% are commercial, and only 0.5% are industrial. The districts within the cluster represented by San Vicente have seen an increase in the Cantonal Human Development Index, positioning them at the top of the ranking. This suggests that economic conditions may not be a barrier for the adoption of new technologies, as is the case in Desamparados. This also explains why even if the district's population growth has slowed, electricity consumption in San Vicente is expected to double by 2050. Due to rising urbanisation rates, the district is likely to face planning challenges on space availability for deploying some technologies. However, the installation of rooftop solar PV along with energy storage systems can be an attractive alternative.

- **District 3 – San Pedro de Montes de Oca:** With the same number of inhabitants as San Vicente, San Pedro has experienced growth in its energy needs driven mainly by commercial activities around the academic sector, as the district hosts many universities. This district is relatively dense, and its buildings are typically old. San Pedro has the highest electricity consumption among the five representative districts, with more than 13 000 electricity customers, of which 80% are residential, 19.7% are commercial, and only 0.3% are industrial. Similar to San Vicente, population growth has slowed but electricity consumption is expected to double by 2050, in this case due to energy-intensive activities in the commercial sector. As the district's Cantonal Human Development Index approaches the top of the ranking in the expectation of growing economic development, the adoption and deployment of new technologies seem feasible and worth exploring.

- **District 4 – San Isidro de Coronado:** While other districts in Costa Rica face urban planning challenges related to their high population density and lack of available land space, San Isidro is notable for having around 18 000 inhabitants distributed over a relatively large area. Its energy needs have not changed significantly over the years; however, the need to electrify activities will likely lead to higher needs in the future. Of the 6 000 electricity customers in this district, 88.5% are residential, 11% are commercial, and only 0.5% are industrial. Although the district's Cantonal Human Development Index has increased, it is not yet at the top of the ranking. Growing economic development, however, indicates that transformations can occur if well-designed policies are in place. The main challenge in this district is not so much land space for placing technologies, but the relatively low potential for solar PV production – the irradiance values are not as high as in other districts within the Greater Metropolitan Area, which may necessitate exploring other technologies.

- **District 5 – San Rafael de Coronado:** This district has the lowest number of inhabitants among the five representative districts, with only around 8 000, as well as the lowest electricity consumption. The district is dominated by farmers, and while the Cantonal Human Development Index remains low, it has increased over the years. Unlike in the other studied districts, the population is expected to grow by 2050, and along with economic development this is expected to increase energy consumption in the future. Of the 3 000 electricity customers in this district, 87% are residential, 7.6% are commercial, and 5.4% are industrial, with the latter dedicated mainly to milk and cattle production. As in San Isidro, the land area is vast, allowing the deployment of technologies that may not be suitable for high-density districts (for example, wind turbines). According to existing studies (Valverde *et al.*, 2015), solar PV generation may be unsuitable due primarily to cloud effects. The use of waste is another technology with great potential given the presence of many cattle factories in this district.

TABLE 5: Selected socio-economic and energy-related variables considered for the analysis

DISTRICT	DESAMPARADOS	SAN VICENTE	SAN PEDRO	SAN ISIDRO	SAN RAFAEL
Population (2018)	37 079	32 146	29 126	18 398	8 266
GDP (USD billon)	0.337284	0.292412	0.264941	0.167355	0.075191
GDP growth to 2035	0.034957	0.031414	0.029875	0.035458	0.043777
GDP growth to 2050	0.032349	0.028841	0.027232	0.03306	0.041184
Population density (2018)	11 212.93	5 964.01	6 197.02	3 579.38	487.67
Electricity demand (GWh)	49.24	65.79	107.18	26.95	8.21
Customers	11 746	12 556	13 258	6 261	2 296
Residential customers	10 378	11 063	10 590	5 536	1 996
Commercial customers	1 323	1 455	2 613	691	175
Industrial customers	45	38	55	34	125
Yearly electricity (GWh)	49.24	65.8	107.19	26.95	8.21
Yearly residential electricity use (GWh)	27.71	35.08	32.46	17.18	6.41
Yearly commercial electricity use (GWh)	19.63	25.42	55.49	8.07	1.48
Yearly industrial electricity use (GWh)	1.9	5.29	19.24	1.7	0.31

Source: Data processed in the context of the analysis, 2020.

3

DECARBONISING THE ENERGY SECTORS AT THE MUNICIPAL LEVEL

Given the high urbanisation rate in Costa Rica and that nearly half of the population resides within the boundaries of the Greater Metropolitan Area, it is necessary that municipalities be part of the country's decarbonisation strategy – the strategy that has been orchestrated and designed at the national level while being implemented with the support and engagement from local authorities and stakeholders. For example, authorities at the local level can put forward initiatives such as planning a "15-minute" city (as proposed by Paris, France) to shift mobility to non-motorised transport. Such initiatives would lead to reduced consumption of fossil fuels, which currently dominate the transport fuel mix in Costa Rica.

Other opportunities exist as well. Even though Costa Rica's electricity demand is well covered under the current Electricity Generation Expansion Plan, strategically it is worth considering diversifying the mix to enhance energy security and hedge against the seasonable variation and climate-induced risks facing hydropower generation. From a technical perspective, local renewable energy sources, particularly solar PV and wind energy, can be tapped into to diversify the power mix, thus enhancing the security of energy supply (IRENA, 2021a).

Renewables can bring numerous benefits to local governments, including improving the quality of life of citizens, contributing to climate mitigation, boosting the local economy and creating jobs, and improving the quality and reliability of the power supply. However, realising these benefits would require a thorough scenario-based evaluation of urban energy development options. This could provide an overall framework for different national authorities to better co-ordinate among themselves, as well as for local governments to utilise, particularly since urban planning needs to be involved.

3.1 Medium- and long-term perspectives

Costa Rica's existing national climate policies provided guidance to construct three scenarios, which are applicable to the five representative districts. The first scenario, *business-as-usual (BAU)*, considers no decarbonisation targets and assumes that fossil fuels will continue to be the main source of energy in the transport and industry sectors. The second scenario, *urban-level NDP*, adopts the targets stated in the National Decarbonisation Plan, scaling them down to the district level using the population and GDP, with the objective of analysing the potential for decarbonisation following the NDP targets with the support of municipalities involved in urban energy planning. The third scenario, *net zero carbon (NZC)*, considers the country's vision to become carbon-neutral by 2050 in line with the NDP, which includes the highest penetration of renewable energy resources in the transport and energy sectors.

Business-as-usual (BAU) scenario

The BAU scenario does not consider energy policies towards decarbonisation. Fossil fuels continue to be the main source of energy in the country, particularly in the transport and industry sectors, and their consumption follows the existing trend. This scenario presents a path dependency future with low penetration of distributed generation and practically no deployment of electric vehicles. Key projections are presented below:

- **Energy sector:** The renewable energy share increases from 27% in 2020 to only 30% in 2050 considering a low penetration of renewables in the energy system. Low electrification in industry by 2050 to replace fossil fuels results in this very limited increase in the share of renewable energy.

- **Residential sector:** If new energy policies are not applied in the residential sector, there will be a small decrease in the renewable energy share due to a slight increase in the use of liquefied petroleum gas (LPG) for cooking. Currently, this sector has an 82% renewable share (electricity), which could decrease 2% by 2050 due to increased use of LPG for cooking.

- **Commercial and public buildings:** The use of LPG for cooking increases here as well, and the sector's current renewable energy share of 93% could drop to 91%.

- **Industrial sector:** Current electrification of the industry sector is 43%, and there would be a substitution of fossil fuels of up to 50% by 2050.

- **Transport sector:** The transport sector remains as it is today, with the vehicle fleet almost 100% based on fossil fuels.

- **Emission reduction:** Emissions in 2018 were 6.73 megatonnes (Mt) of CO_2-equivalent, and without decarbonisation they will grow an estimated 35% by 2050.

Urban-level National Decarbonisation Plan (NDP) scenario

The urban-level NDP scenario considers a full deployment of the policy actions presented in the NDP, scaled down to the district level. It represents a high climate ambition for the country. This scenario shows the pathway towards electrification of the transport sector (public, private and freight) and a highly renewable electricity mix with a high penetration of distributed energy resources. It considers a gradual increase until 2050 of targets, as follows:

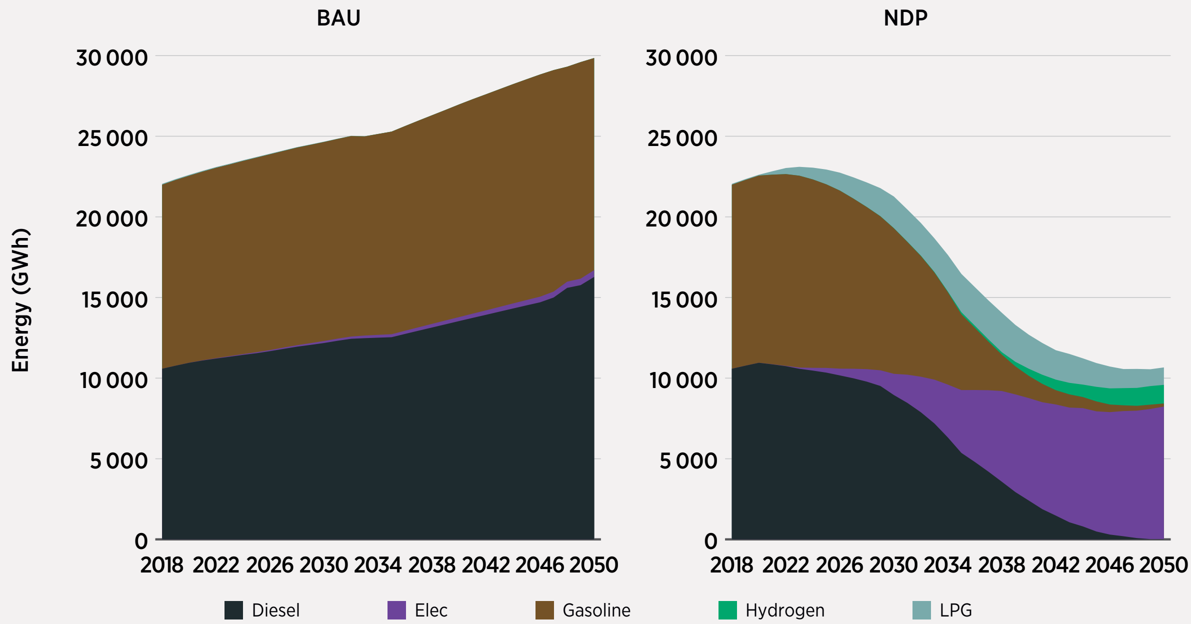
- Total renewable energy share increases to reach 95% of total final energy consumption by 2050.

- Renewable energy share in the residential sector increases to reach 100% of total final energy consumption in the sector by 2050.
- Renewable energy share in commercial and public buildings increases to reach 100% of total final energy consumption in the sector by 2050.
- Renewable energy share in industry increases to reach 80% of total final energy consumption in the sector by 2050.
- Renewable energy share in transport increases to reach 90% of total final energy consumption in the sector by 2050.
- CO_2-equivalent emissions drop 85% by 2050 compared to 2018.

The use of electricity for transport is expected to grow significantly by 2050 in the urban-level NDP scenario, as evidenced by the fuel shares of energy demand at the national level in the transport sector (Figure 14). This scenario also considers the gradual replacement of diesel and petrol with electricity and hydrogen, and a limited penetration of LPG. The scenario also expects a reduction in energy demand due to the greater efficiency of the technologies that use these new fuels in the transport sector.

Decarbonisation of the transport sector is likely to contribute the greatest level of emission reductions and will potentially drive other socio-economic benefits in cities such as lower congestion, fewer accidents and more jobs (IDB and DDP-LAC, 2019; Saget, Vogt-Schilb and Luu, 2020). However, to enable the benefits of an electric transport sector, the electricity system must also evolve. It must ensure high participation of renewable energy sources with deployment of distributed generation in the overall energy system.

FIGURE 14: Energy mix for transport sector over 2018-2050 at the national scale



Source: Based on data from Government of Costa Rica and MINAE, 2019b.

Electrification of the industry sector must also evolve, and enabling conditions should be designed. Figure 15 indicates a growing share of electricity for this sector, which will help reduce overall energy consumption through increased energy efficiency. Petroleum coke, LPG, fuel oil and diesel used in the BAU scenario (without decarbonisation) are gradually decarbonised with low- or zero-emission technologies.

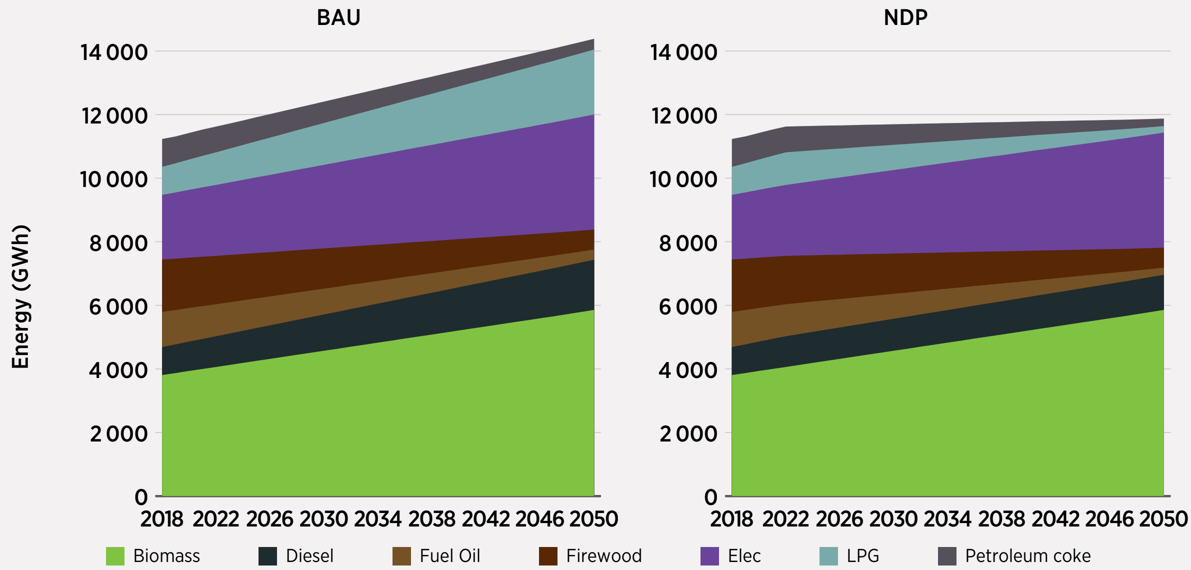
However, to maximise the benefits of electrifying the industry sector, challenges remain. Electrification of this sector may lead to higher energy expenditure for the end users as a result of the lost subsidies granted to the substituted petroleum-derived energy commodities. Therefore, restructuring electricity tariffs to support this technological transition may be required.

In Costa Rican industry, the main fuels that emit greenhouse gases are oil, petroleum coke, diesel and LPG. According to the characterisation of industrial energy consumption provided in MINAE (2019b), the industries that mostly consume these four fuels are the food, metal products and mineral (cement and glass) industries. Large industrial groups require these fuels to operate equipment such as ovens, boilers, emergency power generators, forklifts and internal transport, among others.

Decarbonisation options for the industrial sector have become an important topic in recent years in Costa Rica, and alternatives such as electricity-based heat generation technologies, electricity storage and hydrogen use are currently under discussion. Competitive incentives for electricity and the removal of subsidies for fossil fuels are necessary for this transition.

Finally, in the transport sector, the electric fast passenger train project for the Greater Metropolitan Area is under discussion, and electrification of the current private/public and passenger/cargo vehicle fleet is a subject of national focus. Electrification of the transport sector would not only create additional electricity demand, but potentially provide the flexibility that the future energy system would require, provided that the charging infrastructure for the electric vehicles could be managed smartly to avoid the peak demand surge.

FIGURE 15: Energy mix for industry sector over 2018-2050 at the national scale



Source: Based on data from Government of Costa Rica and MINAE, 2019b.

Urban-level net zero carbon (NZC) scenario

The NZC scenario aims to promote net zero districts. It follows the pathway of the NDP scenario, in terms of electrification of the transport sector (public, private and freight) and residential cooking, while at the same time diversifying the power supply mix by integrating non-hydropower renewable energy sources in the power grids. With energy efficiency improvement measures in the end-use sectors and the decarbonisation of industrial sectors thorough electrification and hydrogen, the scenario presents a more aggressive pathway, illustrated by the following indicators:

- Electrification of 100% of the energy demand for cooking for the residential sector by 2035.
- Electrification of 100% of the remaining fuel-based transport by 2050 compared to the NDP scenario. It includes the same level of penetration of hydrogen technology as stated in the NDP scenario.
- Significant reduction of fossil fuel-based industry, by using electricity for two-thirds of the industrial sector and hydrogen for the remainder (for example, for glass and cement industries).

The efficiency measures follow the high-ambition scenario presented by United for Efficiency, which covers high-consumption appliances, specifically efficiency measures for refrigerators and lighting (United for Efficiency, 2019). In 2018, these appliances represented 41% of residential end-use demand, or more than half of the residential sector energy demand when cooking is included. In the NZC scenario, the transport and industry sectors switch to renewable energy, including green hydrogen and end-use sector coupling technologies.

This scenario includes variations aimed at quantifying the impact of sector coupling strategies deployed in the districts. It considers the potential of vehicle-to-grid with the utilisation of 10% of the battery capacity of parked electric vehicles to provide grid services, and the possibility to optimise importation in relation to local production of hydrogen and on-site storage.

3.2 Evaluation of municipal-level roadmaps

IRENA's Planning Platform for Urban Renewable Energy was employed to evaluate the three scenarios for two key planning horizons (2035 and 2050). The tool provided five different optimal operating points based on multiple objectives for the same target scenario within each district. The five points represent different solutions that are optimal according to multiple objective functions considered (for example, minimisation of the annual costs of the energy system and minimisation of the carbon emissions during operation).

Each Pareto optimal point represents an optimal energy system design and dispatch solution ranging from point 1 to point 5. Point 1 represents the design solution with the least carbon emissions for the minimum costs of the system (operating expenditures and capital expenditures), while point 5 presents the least-cost solution for the minimum carbon emissions. Each solution provides, for each district, a system design and operating strategy for an optimised portfolio of integrated energy systems to supply the energy demand of the district. Each operating point considers different requirements for the deployment of technologies; thus, they present different costs and efficiencies.

FIGURE 16: Share of renewable energy in total final energy consumption, by district, for the BAU scenario and the low-carbon NDP and NZC scenarios

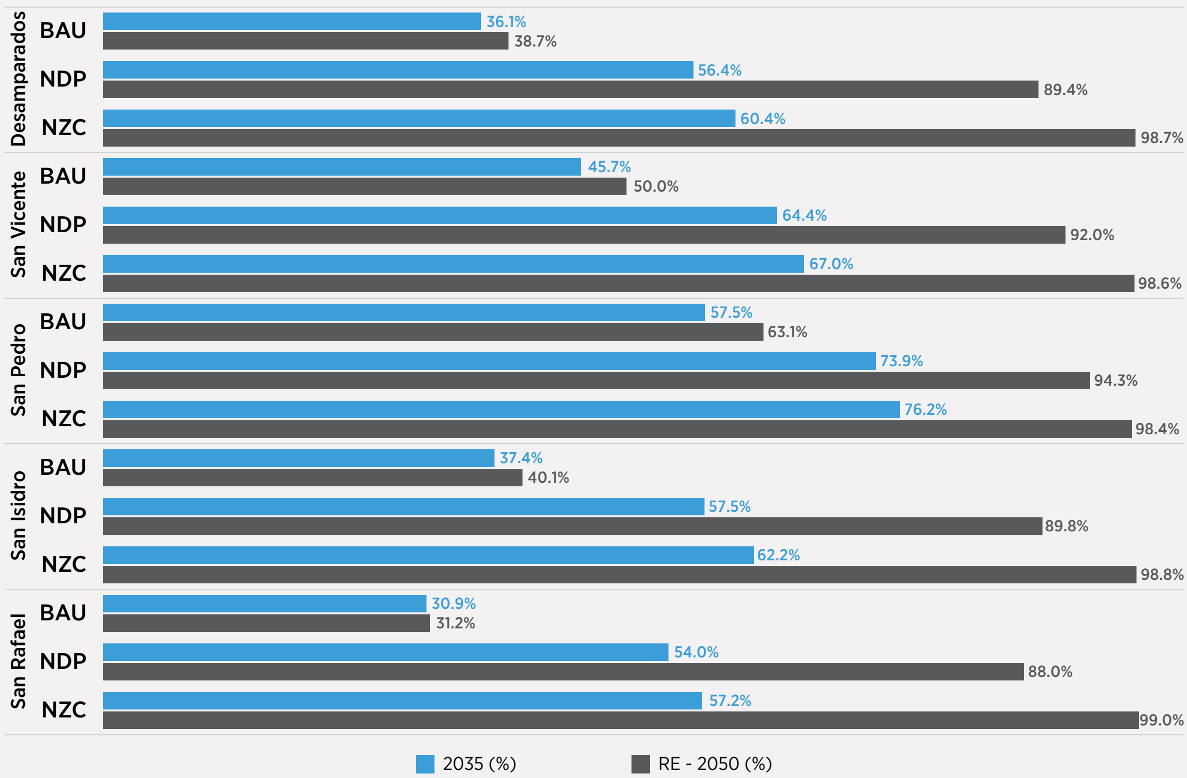


Figure 16 presents the share of renewable energy in total final energy consumption for each of the five districts for the optimised carbon emission reduction (reflecting point 5: least cost for minimum emissions). It illustrates the importance of policies and measures taken at the city level and their impact on achieving the targets. The fluctuation in the renewable energy share from one district to another is greater in the BAU scenario compared to the NDP and NZC scenarios, reflecting the impact of optimising the supply side at the district level with multi-energy carrier integrated systems. While it is possible to reach near net zero carbon in 2050 in all districts, only adequate urban energy planning combining different efficiency and system integration measures for the demand and supply sides would allow complete decarbonisation of the districts.

Medium-term planning (2035)

It is technically possible to reduce emissions in the medium term (Figure 17). The higher the reduction in emissions, the higher the total cost per capita per year, as more zero-emission technologies are needed. Most operating points in the no-policy (BAU) scenario lead to emissions that are higher than the values projected for 2035 in Costa Rica's Nationally Determined Contribution (NDC) (about 1.6 tonnes of CO_2 per capita assuming a linear extrapolation). In the BAU scenario, the optimised solutions provided on the supply side within the technological scope of the study cannot, in most of the cases, match the NDC's targets, except for the district of San Rafael, which can provide a high share of renewable energy for a contained demand.

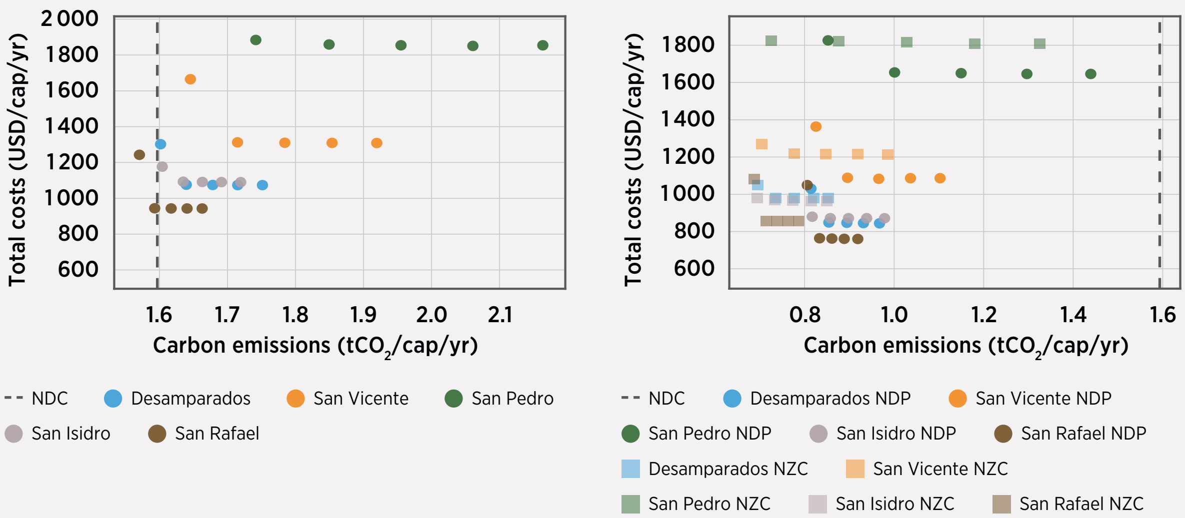
Conversely, all the optimised supply-side solutions deployed at the urban level in the NDP scenario lead to lower emissions than the NDC goal by 2035. The NZC scenario makes it possible to further decarbonise the districts by an average of 10-15% compared to the NDC scenario. This is notable, as Costa Rica has committed to reducing its emissions by mid-century.

Deploying low-carbon technologies to reduce emissions in operating point 5 requires higher investments, as the cost of these technologies is currently high (although their cost-effectiveness is increasing rapidly due to economies of scale). Decarbonising San Pedro (and most likely the districts within the same cluster) leads to higher total costs per capita per year compared to the other districts. This is likely due to the high urbanisation level of the district, which leads to challenges in deploying certain technologies.

Conversely, San Rafael (and other districts with low population density such as those within cluster 5) has the lowest total costs. Districts with lower density require less investments to reach a low-emission target, while having higher decarbonisation potential through the deployment of high renewable energy generation capacity. While the results for all districts are discussed in the sections that follow, illustrations will focus on the two extreme districts: San Pedro and San Rafael.

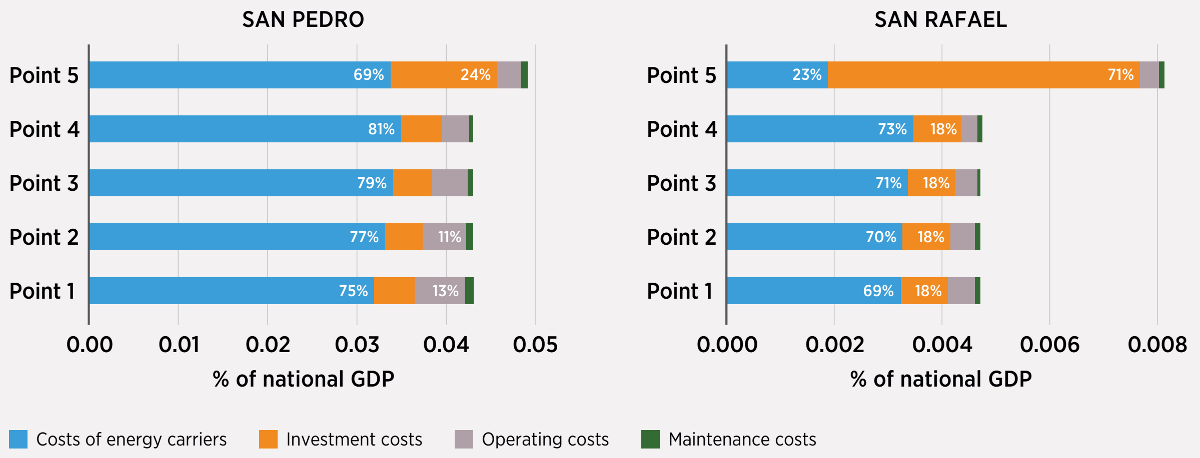
Although decarbonising requires investments in renewable energy and sector-coupled technologies, the operational and maintenance costs are typically lower. The benefits could be even greater if the analysis also considered the health savings from lower emissions, as well as the increased productivity of cities due to reduced traffic congestion and accidents and to greater development and use of public transport (IDB and DDP-LAC, 2019). Figure 18 presents the energy carrier costs (imported electricity, oil derivatives, LPG, etc.), infrastructure costs, and operational and maintenance costs associated with energy use for space heating and cooling, electricity for electro-mobility, and electricity for all other uses in residential, commercial and industrial buildings, all normalised with respect to the district's GDP.

FIGURE 17: Comparison of the BAU scenario (left) and the low-carbon NDP and NZC scenarios (right), showing optimisation results for the medium term (2035), with the trade-off between CO_2-equivalent emissions and costs



Note: The figures show optimal points 1 to 5 from right to left, reaching lower carbon emissions with optimal point 5.

FIGURE 18: Cost breakdown in 2035 for the two extreme districts



Note: The analysis considers only costs associated with energy consumption for space heating and cooling, electricity for electro-mobility (if applicable), and electricity for all other uses in buildings and industry.

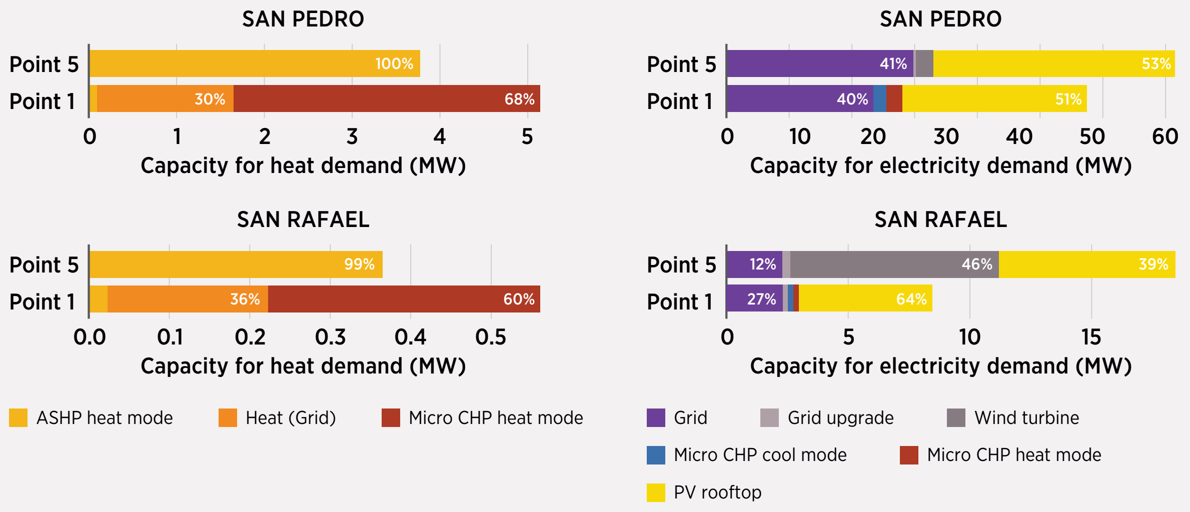
The equivalent annual costs are higher in operating point 5 for all decarbonisation scenarios due primarily to the electrification of the transport and industrial sectors required to lower the respective emissions. This implies that reaching the least emissions possible requires higher investments in electro-mobility and electrification of heating and cooling in buildings and industry. However, these costs are lower in all the other operating points despite reaching high electrification of these sectors.

Investment costs in operating point 5 for all districts except San Pedro are at least double the costs in all other operating points (Figure 18). This is due to the deployment of technologies that are currently expensive in Costa Rica (for example, air-source heat pumps and energy storage systems). However, the results indicate that these technologies have the potential to help meet the decarbonisation goal within the districts by combining high-efficiency technology and the use of local renewable energy potential.

To meet the electricity needs of buildings, Figure 19 provides an overview of the capacity required for each operating point and per district. Rooftop solar PV systems were found to be the most cost-effective technology to enable the transition towards decentralised electricity generation in the representative districts. This is in line with recent global trends, as the cost-effectiveness of this technology has increased greatly in the last decade and will likely continue to increase (García de Fonseca, Parikh and Manghani, 2019).

In operating point 5, the combination of wind turbines together with solar PV systems reduces the impact of seasonality associated with hydropower-dominated grid electricity, maintaining the lowest emissions of the electricity generation. The penetration of wind turbines is greater in San Rafael, and most likely also in other less-dense districts that have larger areas for turbine deployment. Micro combined heat and power (CHP) appears in operating point 1, similarly to points 2, 3 and 4, demonstrating the effectiveness of co-generation at the building or community level, increasing the efficiency of traditional electricity-driven heaters or air conditioning systems. Replacing electric heaters and air conditioners with air-source heat pumps achieves a reduction in carbon emissions.

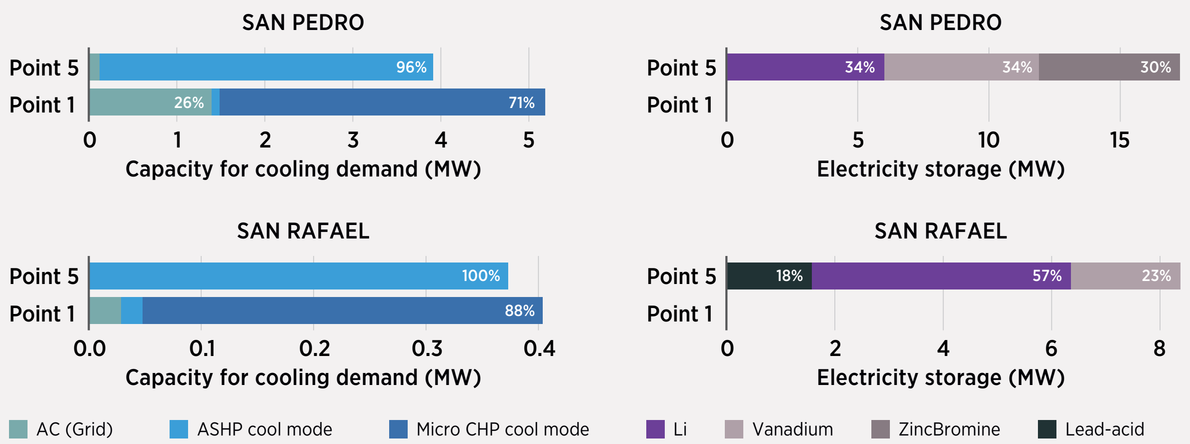
FIGURE 19: NDP scenario showing the capacity needed in 2035 for (a) heating systems in buildings and (b) electricity generation in buildings, for the two extreme districts



The combined results highlight the potential of solar PV systems to support the transition towards decarbonisation in cities. They also illustrate that other technologies are emerging that will enable the change needed to meet net zero emissions in 2050 while bringing socio-economic benefits to city residents (IRENA 2020b; IRENA 2014).

The penetration of new technologies to meet the growing electricity demand in buildings (considering also heating and cooling requirements) in the operation point with the least emissions (point 5) is complemented with the deployment of energy storage systems to reduce the intermittency of these technologies and to enable more resilient operation of the electricity grid. As highlighted in Figure 20, the penetration of energy storage systems is highly correlated with the penetration of high volumes of energy from solar PV systems (operating point 5).

FIGURE 20: NDP scenario showing the capacity needed in 2035 for (a) cooling systems in buildings and (b) energy storage systems, for the two extreme districts



In addition, the results show that lithium-ion batteries are the most cost-effective due to their efficiency and cost. While vanadium batteries are also found to bring benefits in Desamparados and San Vicente districts, their deployment typically leads to higher total costs.

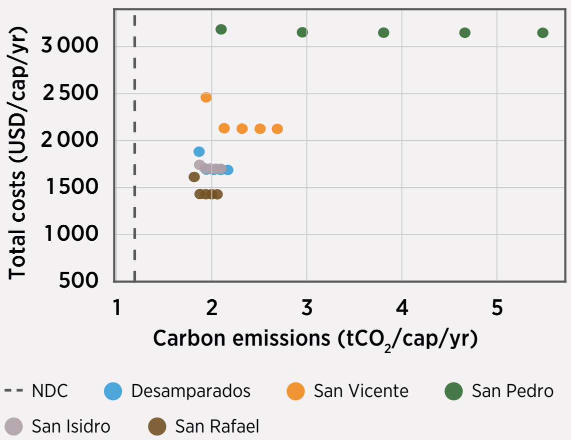
Long-term planning (2050)

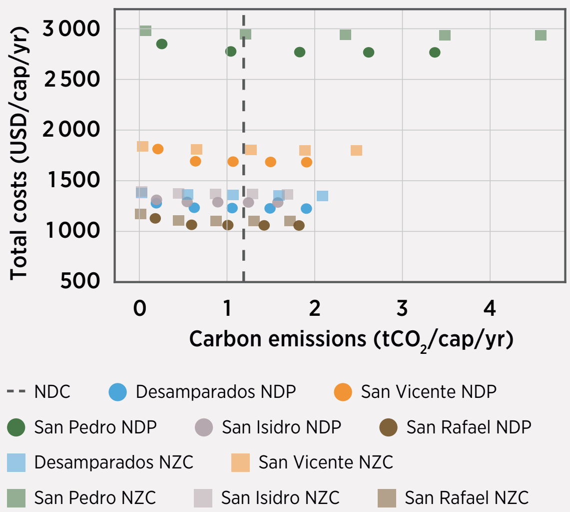
Figure 21 provides an overview of the results for the 2050 horizon. While the NZC scenario brings higher emission-saving potential at higher costs compared to the NDP scenario, both high-ambition scenarios provide carbon emission savings as well as cost benefits compare to the BAU scenario. Following the trend for 2035, San Pedro will require the highest total investment, due to the higher population density and the scarcity of area for installing the most cost-effective technologies. Less-dense cities, such as San Rafael, will have lower total costs in the long term, taking advantage of the highest renewable energy potential for deploying combined wind and solar technologies.

The figure highlights that, despite the combination of technologies, the NDP scenario leads to lower total costs than the BAU scenario. This suggests that decarbonising will result in lower costs and higher benefits associated with a low- or zero-emissions city.

The electricity generation capacity needed to meet the districts' demand in 2050 is expected to increase compared to the 2035 level, partly because the growing adoption of air-source heat pumps for providing heating and cooling services thanks to higher energy efficiencies and the resulting the lower carbon emissions (Figure 22). In addition, highly dense cities such as San Pedro will have the highest electricity demands in both scenarios. Rooftop solar PV has a higher capacity in the BAU scenario for all districts (except for less-dense cities such as San Rafael). These systems, combined with wind turbines, contribute substantially to reaching the decarbonised pathway. Adopting waste-to-energy incinerators (waste boilers) for energy

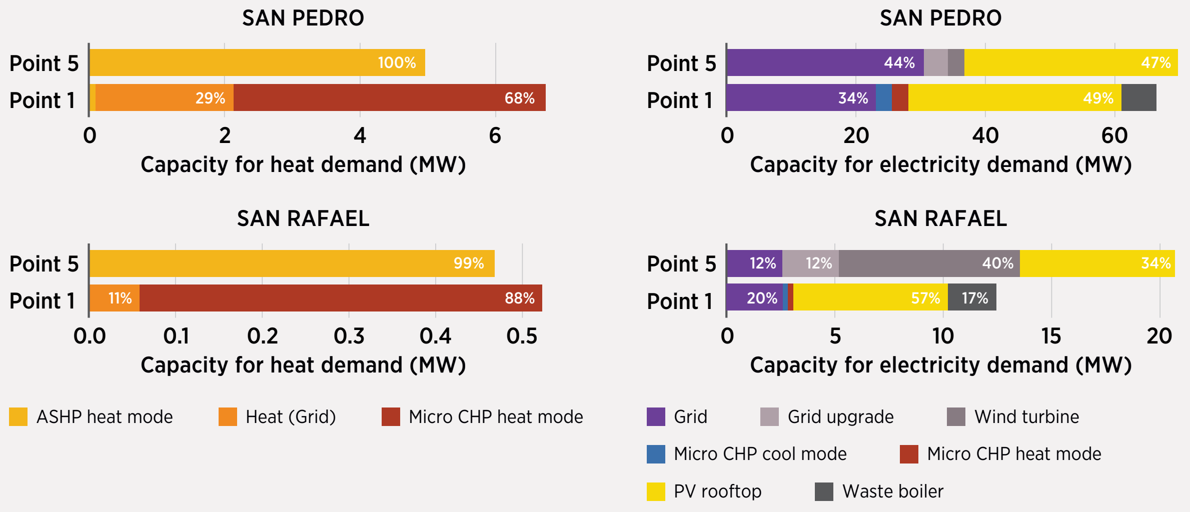
FIGURE 21: CO_2-equivalent emissions and costs in 2050 for the five districts under the (a) BAU scenario and (b) low-carbon NDC and NZC scenarios





Note: The figures show optimal solution points 1 to 5 from right to left, reaching lower carbon emissions with optimal point 5.

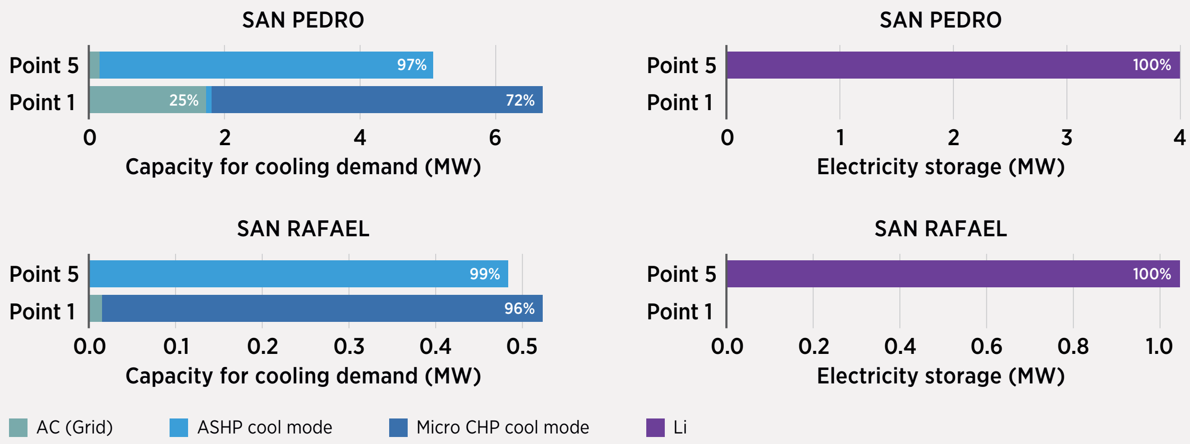
FIGURE 22: NDP scenario showing the capacity needed in 2050 for (a) heating systems in buildings and (b) electricity generation in buildings, for the two extreme districts



production also presents a solution, particularly as these promote the use of waste and a circular economy along with other benefits. It can also be observed that operating point 5 shows a smaller installed capacity as far as heating is concerned due to the high efficiency of the air-source heat pump technology adopted in this operation strategy.

Energy storage systems will be part of the technology mix to enable the energy transformation of cities (Figure 23). The penetration of storage varies by city and depends not only on the share of variable renewables in the power mix, but also on the availability of space. Since San Pedro is a highly dense city with high participation and support from the grid, the adoption of energy storage there was found to be lower in 2050 compared to 2035, due mainly to high electricity

FIGURE 23: NDP scenario showing the capacity needed in 2050 for (a) cooling systems in buildings and (b) energy storage systems, for the two extreme districts



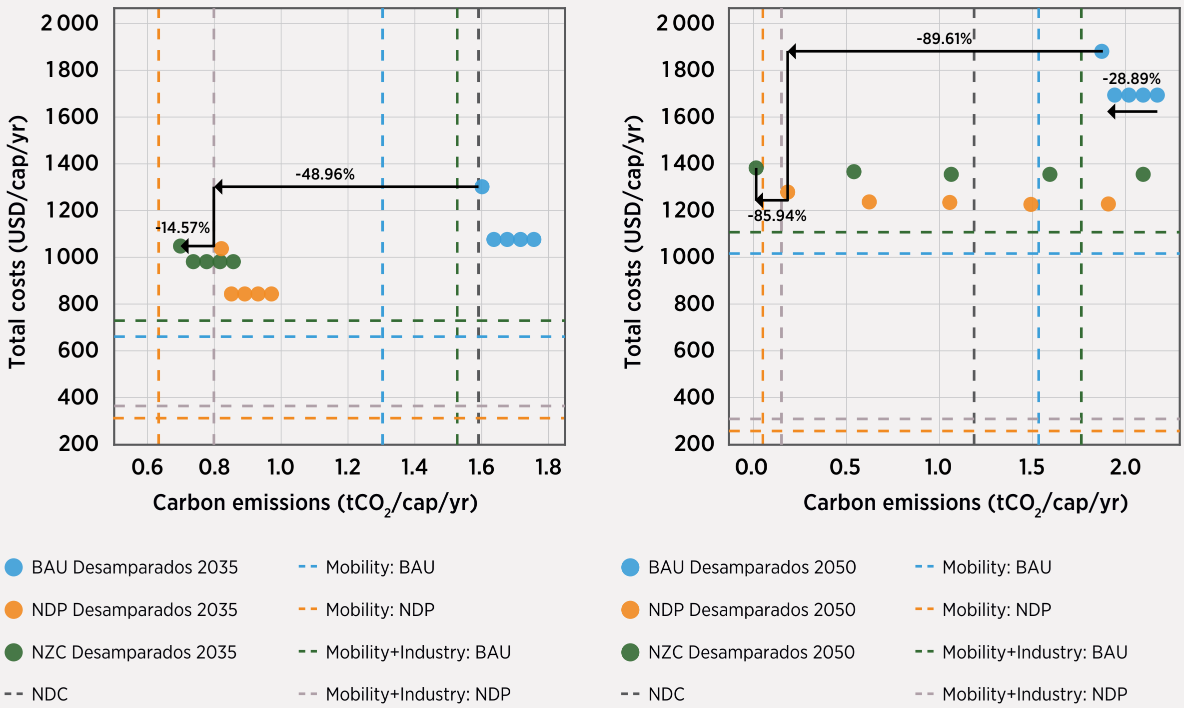
demand that calls for importation to the district rather than storage capacity. Alternative scenarios, presented in the following section, include sector coupling enablers (such as an optimised hydrogen strategy, relevant to the NZC scenario) as well as vehicle-to-grid potential through the use of battery capacity made available from electric vehicles.

3.3 Alternative scenarios

To cope with the electrification of the transport sector and with industry decarbonisation strategies, cities will require a mix of technologies that must be integrated into multi-source energy systems. This might raise challenges for highly dense cities that face growing energy consumption as well as spatial constraints for installations. Desamparados is a dense district in Costa Rica, making it an interesting case study for the three evaluated scenarios and proposed alternatives.

Figure 24 provides an overview of the operating points of all scenarios for Desamparados for the years 2035 and 2050. The contributions to costs and emissions of the transport and industry sectors are shown in the dotted lines (the emissions and costs related to electricity-driven solutions for transport and industry are excluded from the dotted lines). The expected yearly emissions per capita are represented in the black line, labelled NDC. This was obtained by linearly interpolating the values included in MINAE (2015) for the years 2030 to 2050.

FIGURE 24: Comparison of urban energy planning strategies for the district of Desamparados in 2035 and 2050



Note: The lines corresponding to mobility and industry exclude the consumption of electricity for both sectors, which is included within the costs and carbon emissions of the energy system represented by the point.

The figure presents a number of possibilities for fulfilling the NDC targets. In addition, the benefit represented by going from the BAU scenario to the NDP scenario in percentage terms is included with arrows. The NZC scenario was also included, and it is noted that, for 2035, the point of minimum carbon could be reduced by up to an additional 15% with respect to the NDP scenario. This point of operation of the energy system would lead Costa Rica to carbon neutrality in the medium term but would require greater deployment of renewable energy in the remaining years of the 2050 horizon, mainly to cope with electrification of the transport sector.

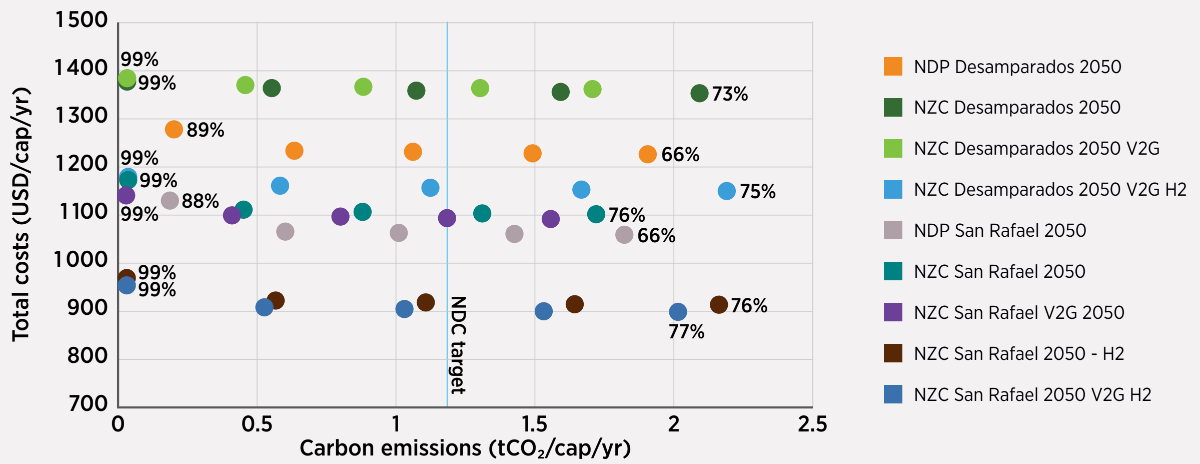
Similar to the other districts and within the technological scope of this study, the district of Desamparados would unlikely meet the NDC target by 2035 by solely deploying supply-side measures, as in the path of the BAU scenario. Furthermore, the BAU scenario appears to be a more costly pathway when considering the inclusion of distributed energy systems within the district. The carbon emissions related to supplying energy for buildings, industry and mobility can be lowered by a factor of 2 to 3 when respectively considering the NDP or the more aggressive NZC scenario. Most of the optimal points of the NDP and NZC scenarios can meet the NDC carbon emission target by 2050.

Alternative technological scopes for the NZC scenario were considered, in which sector coupling technologies and strategies are taken into account and their impact is quantified. The alternative options for the NZC scenario analysed in the following section include flexibility potential for the districts through sector coupling technologies, as follows:

- 10% of the battery capacity of parked electric vehicles can be used by the optimisation problem as storage capacity in a vehicle-to-grid configuration.
- Hydrogen technologies are adopted to provide flexibility. The model optimised local production (versus importation) of hydrogen, along with storage capacity and dispatch, considering the requirements for hydrogen applications in the end use sectors.

Combinations of those alternative scenarios are presented in Figure 25, highlighting the capabilities to reduce costs (by around 15%) and emissions through increased local storage capacities, the vehicle-to-grid strategy, and the possibility of on-site production of hydrogen.

FIGURE 25: Alternative scenarios considering vehicle-to-grid and hydrogen optimal strategies

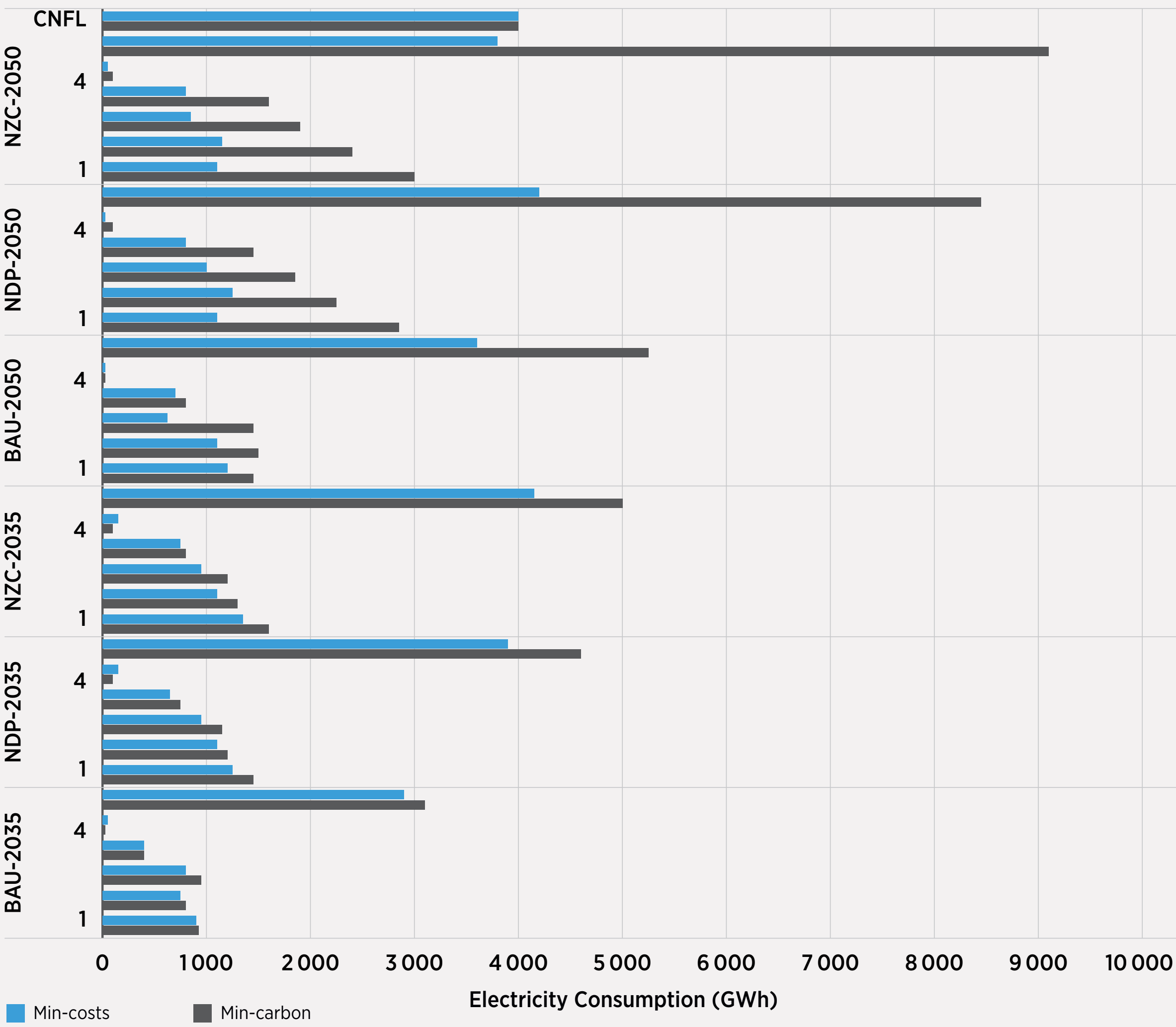


Another finding of the study highlights the cost effectiveness of storage solutions for less-dense districts such as San Rafael, where increasing the storage capabilities decreases the overall costs of the energy supply. For denser districts, the benefit of a storage strategy versus grid upgrade is lower, given a lower renewable energy potential in relation to higher electricity demand. A community-scale analysis can be developed to further assess the role of storage in this context.

3.4 Implications for the national grid infrastructure

The electricity imported from the grid is higher in the NDP scenario, given increased electricity demand as a consequence of electrification of the mobility sector. At the utility scale, the insights from the study provide quantification of the requirement from the national grid in terms of electricity imported to the districts, for the different solutions (Figure 26). These results account for the potential of a renewable-based distributed energy system deployed in the districts of Costa Rica and provide insights for the local generation, transmission and distribution utilities to consider when developing grid expansion planning at the regional or national scale.

FIGURE 26: Grid electricity consumption in 2035 and 2050



In the short term, grid imports to the districts oscillate around today's value for the cost-minimal solution, despite the increase in electrification. For carbon minimisation, electricity import to the districts increases by up to 25% compared to today's electricity demand. In the long term, electricity demand will grow in the net zero carbon districts scenario, increasing the need for renewable electricity import to the districts. Local renewable energy sources through distributed energy systems can meet part of the increased electricity demand that would come largely from electrification of the transport and industry sectors. Further analysis can be performed on the potential to optimise energy demand and supply by considering inter-district energy exchange, the role of storage at the community scale and demand-side management measures.

3.5 Extrapolation to the CNFL area

With the application of the clustering analysis, the district-level results were extrapolated to the CNFL area. This provides an estimate of the potential for renewable energy deployment within the area. For the optimal decarbonisation pathway, considering the minimum carbon emissions solutions leads to a potential installed renewable energy capacity of 1.7 gigawatts (GW) to 1.9 GW of solar PV and 100 MW to 200 MW of wind power, combined with the deployment of options providing system flexibility in 2050, including 26 MW to 80 MW of electrolyser capacity (13 MW fuel cell) and up to 1 GWh of electricity-based storage capacity. This provides an estimate of the renewable energy potential that can be harvested in and around the city as well as in the region.

Total costs per capita in cities within cluster 3 (for example, San Rafael of Escazú, Guadalupe of Goicoechea, San Pedro of Montes de Oca, Curridabat and Tres Rios) will tend to be higher than in the other clusters. Cities in cluster 2 will have the second highest total cost per capita, followed by cities in cluster 4 and cluster 1. Cities in cluster 5 will tend to have the lowest total cost per capita. There is a close correlation between the total costs per capita and the population density – the higher the density, the higher the total costs.

Despite the planning horizon, the results also highlight that the scenario with decarbonisation typically leads to lower total costs. The deployment of rooftop solar PV systems along with network upgrades to enable their integration was found to be key across all cities. While wind turbines could also help in the decarbonisation of cities, this technology was found to be suitable primarily for cities within cluster 5. Air-source heat pumps are a technology with great potential to reduce emissions, and lithium-ion batteries will enable greater integration of renewable energy sources.

Table 6 provides the total emissions per capita in each of the five districts. As expected, the scenario with decarbonisation targets leads to operations with much lower emissions than the BAU scenario.

The population of cities can be used to reflect the total costs and emissions for each district, as well as for the total CNFL concession area. Table 7 highlights that decarbonising the CNFL concession area by 2050 will require total costs equal to 2.5% of the country's GDP. Notably, the BAU scenario leads to higher total cost ranges. Moreover, there are extra benefits associated with the deployment of renewables that have not been quantified in this analysis. Table 8 indicates that the deployment of renewable energy sources combined with an electrification strategy enables a reduction of up to around 5 Mt of CO_2 compared to the BAU scenario. This reduction is achieved primarily thanks to the deployment of renewables and the electrification of the transport sector.

TABLE 6: Total per capita CO_2 emissions of the energy systems in the five district clusters for 2035 and 2050

CARBON EMISSIONS (TONNES OF CO_2-EQUIVALENT PER CAPITA)						
CLUSTER	BAU 2035	NDP 2035	NZC 2035	BAU 2050	NDP 2050	NZC 2050
1	1.60 - 1.75	0.82 - 0.97	0.70 - 0.86	1.87 - 2.17	0.19 - 1.91	0.03 - 2.09
2	1.64 - 1.92	0.83 - 1.10	0.70 - 0.99	1.94 - 2.69	0.21 - 1.91	0.04 - 2.48
3	1.74 - 2.16	0.85 - 1.44	0.72 - 1.33	2.10 - 5.48	0.26 - 3.37	0.07 - 4.58
4	1.60 - 1.72	0.82 - 0.98	0.70 - 0.85	1.87 - 2.10	0.20 - 1.58	0.03 - 1.69
5	1.57 - 1.66	0.81 - 0.92	0.69 - 0.79	1.82 - 2.06	0.18 - 1.82	0.02 - 1.72

Note: The table presents the variation between emissions to cost-optimal solutions.

TABLE 7: Total costs of the energy system in the five district clusters for 2035 and 2050

TOTAL COSTS (% OF NATIONAL GDP)						
CLUSTER	BAU 2035	NDP 2035	NZC 2035	BAU 2050	NDP 2050	NZC 2050
1	1.14 - 1.38	0.89 - 1.09	1.04 - 1.11	1.1 - 1.23	0.8 - 0.83	0.88 - 0.9
2	0.77 - 0.99	0.64 - 0.81	0.72 - 0.75	0.79 - 0.91	0.62 - 0.67	0.67 - 0.68
3	0.53 - 0.54	0.47 - 0.52	0.52 - 0.52	0.5 - 0.51	0.44 - 0.46	0.47 - 0.48
4	0.58 - 0.63	0.46 - 0.47	0.51 - 0.52	0.57 - 0.58	0.43 - 0.44	0.46 - 0.47
5	0.07 - 0.09	0.06 - 0.08	0.06 - 0.08	0.07 - 0.08	0.05 - 0.06	0.05 - 0.06
Total	3.09 - 3.63	2.52 - 2.97	2.85 - 2.98	3.03 - 3.31	2.34 - 2.46	2.53 - 2.59

Note: The table presents the variation between emissions to cost-optimal solutions.

TABLE 8: Total CO_2 emissions of the energy system ($MtCO_2e$) in the five district clusters for 2035 and 2050

CARBON EMISSIONS ($MtCO_2e$)						
CLUSTER	BAU 2035	NDP 2035	NZC 2035	BAU 2050	NDP 2050	NZC 2050
1	1.35 - 1.48	0.69 - 0.82	0.59 - 0.73	1.63 - 1.90	0.17 - 1.67	0.03 - 1.83
2	0.78 - 0.91	0.39 - 0.52	0.33 - 0.47	0.96 - 1.34	0.10 - 0.95	0.02 - 1.23
3	0.40 - 0.49	0.19 - 0.33	0.16 - 0.30	0.45 - 1.17	0.06 - 0.72	0.01 - 0.98
4	0.68 - 0.73	0.35 - 0.42	0.30 - 0.36	0.84 - 0.94	0.09 - 0.71	0.01 - 0.76
5	0.09 - 0.10	0.05 - 0.05	0.04 - 0.05	0.12 - 0.14	0.01 - 0.12	0.00 - 0.11
Total	3.30 - 3.71	1.67 - 2.14	1.42 - 1.91	4.00 - 5.49	0.43 - 4.17	0.07 - 4.91

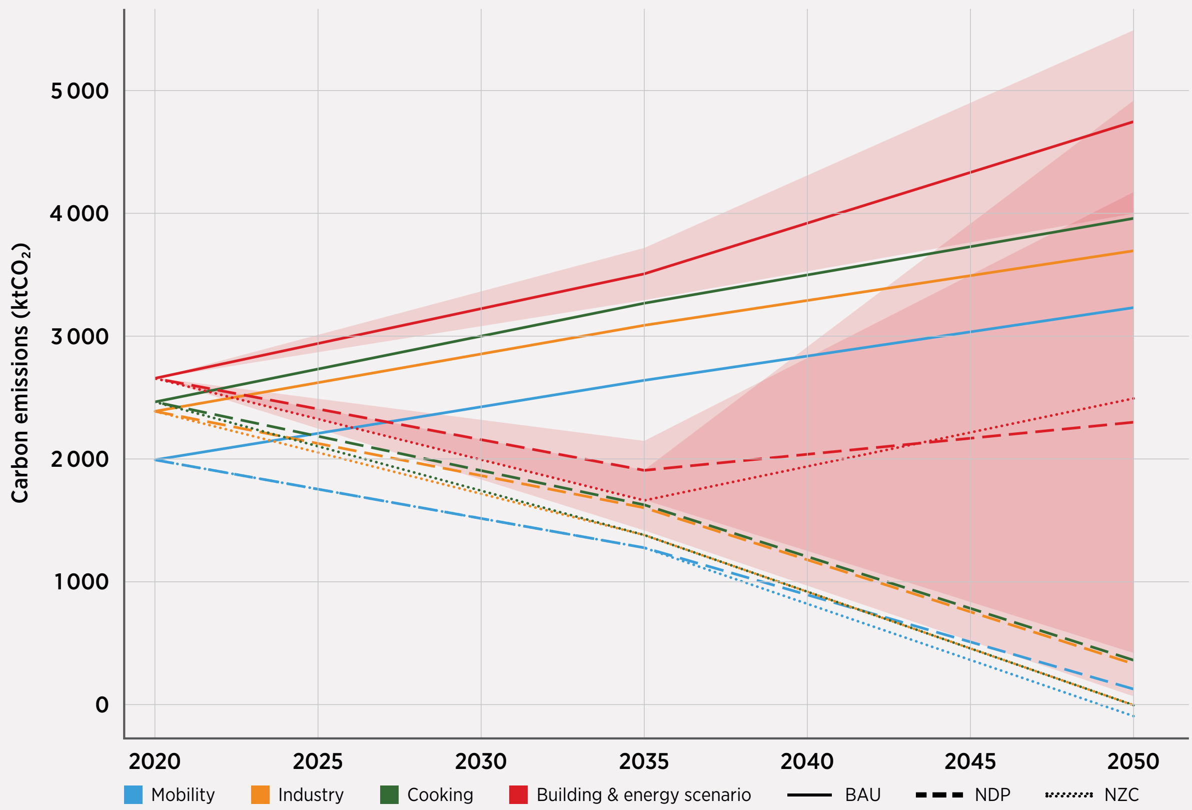
Note: The table presents the variation between emissions to cost-optimal solutions.

The population for each city within the CNFL concession area and the emissions for each district were used to estimate the carbon emissions reductions for the NZC scenario in 2050 compared to the no-policy (BAU) scenario. Since all cities deploy zero-emission technologies along with energy efficiency measures in the NZC scenario, the reduction of emissions is significant (particularly for highly dense cities) and is attributed mainly to the transport sector. Cities such as San Rafael have the least reduction of emissions mainly because of the smaller population size and lower number of vehicles.

The carbon emissions are quantified for the medium-term and long-term scenarios, stacked by sector and scenario in Figure 27, starting with the mobility, industry and buildings sectors, which also include the generation of local energy, such as electricity and hydrogen, based on the scenario. The shaded areas in the figure represent the emissions for the different objective functions, with the lower end representing carbon minimisation. The maximum emission reduction achieved per scenario is highlighted on the figure, with the name of the scenario juxtaposed to the final carbon emissions reached in 2050.

The NDP scenario provides a potential reduction in carbon emissions of 50% compared to the BAU scenario. Between 83% and 87% of the emissions savings, for 2035 and 2050 respectively, are achieved through the electrification of transport combined with the development of public transport. The NZC scenario provides a further 15% reduction in carbon emissions in 2035 through efficiency measures for appliances and by switching LPG use in cooking to electricity-driven systems for buildings.

FIGURE 27: Carbon emissions by sector, 2020-2050, for the CNFL concession area



3.6 Key challenges and proposed actions

To implement the district- or city-level decarbonisation solutions as a contribution to the national plan in Costa Rica, a number of key challenges would need to be addressed.

Strengthen institutional co-ordination. Urban energy planning requires the co-ordination of a multitude of fields, stakeholders and information in order to reach a diversity of sustainability objectives and trade-offs. While architects and planners must rethink buildings and spaces, local and regional authorities need to adapt organisational procedures; lawyers and politicians need to adjust legal texts and policy; and utilities must develop profitable business models.

In addition, at the national level the co-ordination among different relevant ministries needs to be strengthened to address the issues around urban development and the associated growth in energy demand in a co-ordinated fashion and to deliver optimal solutions to both issues at the city level. Urban energy demand is substantially affected by urban planning and forms, while urban planning offers opportunities to integrate local renewable-based generation into cities.

To achieve this, the institutional barriers that limit the penetration of renewable energy generation facilities in distribution networks should be removed.

Co-ordinate charging of fleets to avoid stress on the power grid. The charging of electric vehicles during periods of maximum electricity demand may pose challenges to the operation of distribution networks, if smart charging schemes are not put in place. Distribution network operators must study the interactions between these technologies. Thus, detailed technical studies must be executed to understand the network's ability to host the new technologies. Importantly, charging schemes to mitigate potential technical problems must be developed to allow high penetration levels of electro-mobility. The technical challenges and the cost effectiveness of these schemes must be assessed.

Develop a tariff structure for the electrification of the industrial sector. There have been discussions in the country on the tariff for the industrial sector. The electrification of industry activities will require reviewing the tariff to ensure the cost-effectiveness of applications. For example, electrical chillers will increase electricity demand, and this will likely lead to a higher tariff unless new tariff schemes are deployed to offset the fuel switch from subsidised fossil fuels to renewable electricity.

Interestingly, the taxation on fossil fuels used for the transport sector has represented around 11% of government revenue – a typical case of cross-subsidisation. Electrification of the transport sector will reduce fossil fuel consumption, and consequentially this revenue. However, on-site renewable electricity generation facilities can usually bring more local job opportunities and economic activities, thus generating economic gains. Therefore, it would be advisable to review the economics of shifting away from fossil fuel to renewable electricity in a holistic approach.

Local governments manage or oversee all city activities and developments; thus, they should play a central role in determining the energy and carbon emission scenarios of their cities. They also have direct access to their citizens and are best positioned to know their needs and to influence their behaviour. Municipalities can also undertake significant energy savings in their own operations, thereby saving money, setting a good example and even testing new technologies (ICLEI, 2009). Based on this study, the following actions were put forth for local authorities in general in the country.

Create a greenhouse gas inventory to enable prioritisation of actions based on mitigation targets. Only 12 municipalities in Costa Rica have a greenhouse gas inventory (DCC, 2018), while another 11 are starting this process. The remaining municipalities should also be part of this initiative, as it provides a clear indication of the type of energy-related measures that will bring the greatest emission reduction benefits.

Design an integral long-term strategy with intermediate goals and short-term policy instruments. The design of a long-term strategy is essential for better planning the transition towards energy efficiency, electrified transport and higher shares of renewable energy sources. This strategy must include mid-term goals to measure progress in the interim. In addition, quantitative analysis that roadmaps the technological transformation along with its costs and benefits will enable a better decision-making process. The long-term strategy must also account for multiple development objectives. By incorporating different societal points of view, it is more likely to be accepted by the community, although this brings an extra layer of complexity. Co-ordination with local residents and industry within the city has to be considered in this long-term energy strategy.

Use advanced planning tools to inform transformational plans. GIS-based tools enable capturing the particularities of cities for planning the energy transition, as they can be used to better understand the relation between energy generation and demand needs (Valverde *et al.*, 2017). They also allow a better allocation of renewable energy sources accounting for space limitations. The planning of other key infrastructure such as the building design and waste management activities in cities can also benefit from GIS tools. Temporal granularities and spatial boundaries must be accounted for when applying these tools, given the unique geographic and production patterns of renewables such as wind and solar.

Involve local governments in the provision of services to bring benefits to city inhabitants. Local governments in the country have little or no participation in the provision of basic services including water, integrated waste management, electricity and transport. However, they manage or oversee all city activities and developments. It is therefore recommended that they be involved in the planning and design of these services as well as in transport planning across and within the city.

Local governments should prioritise those energy-related cross-sector projects that could create synergies, improve the overall efficiency of resource management, and show significant cost savings, while building a more sustainable urban system.

4

CONCLUSIONS

This report explored the plausible decarbonisation pathways for the Greater Metropolitan Area of the Central Valley in Costa Rica. This represents a potential action that sub-national governments can take to assist the national government in implementing the National Decarbonisation Plan, given that the country's carbon emissions come mostly from the transport, industry and buildings sectors. Additionally, locally available renewable energy potential, particularly solar PV and wind energy, can in the long run be tapped into to diversify the power mix, thus enhancing the security of energy supply from a technical perspective.

The study also found that sector coupling technologies and strategies will play a critical role in keeping the energy system operation reliable and stable while diversifying the energy supply by scaling up variable renewable energy sources. In this regard, through applying the Planning Platform for Urban Renewable Energy – a tool that IRENA has developed – different coupling options for the five districts located within the concession area of the state-owned power utility CNFL were evaluated as part of the overall analytical results, based on which the different scenarios were constructed. The granular temporal and geospatial analyses for those representative districts were conducted and the ensuing extrapolation to the Greater Metropolitan Area was taken to understand the potential impact on the entire area. The results show that the resultant emission reduction would be reached by around 90% by 2050 compared to BAU is technically possible in the NDP scenario.

Crucially, the results demonstrate that it is possible to reach a 100% reduction in this same period in the NZC scenario. In other words, there are no technological barriers to meeting high-ambition targets by 2050. Notably, decarbonisation of the transport sector is likely to contribute the greatest level of emission reductions and will potentially drive other socio-economic benefits in cities such as lower congestion, fewer accidents, improved air quality and more jobs. Overall, this study has created a link between the National Decarbonisation Plan and the actions that local governments can take to contribute to the national carbon neutrality goal by 2050.

However, materialising the net zero scenarios described in the study would require the removal of institutional and regulatory barriers to allow sub-national governments to devise specific plans and actions based on their localities. At the national level, the study results would enable better co-ordination between urban planning and energy planning.

With the support of the planning platform to facilitate the decision-making process for long-term urban energy planning in cities – by analysing and optimising the technical and financial viability of integrating renewable energy technologies – sub-national governments could undertake informed planning to maximise the use of renewable energy potential with the support of sector coupling options to meet their energy demand. This will not only assist them in contributing to the national climate objectives, but also enhance their climate resilience capacity as well as benefit the local economy and people.

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