RICHENEL BULBAAI

TOWARD 100% SUSTAINABLE ENERGY PRODUCTION AND A STRUCTURAL DECREASE IN ENERGY DEMAND:

CURAÇAO, AS A CASE STUDY OF SMALL ISLAND DEVELOPING STATES

**TOWARD 100% SUSTAINABLE ENERGY
PRODUCTION AND A STRUCTURAL
DECREASE IN ENERGY DEMAND:
CURAÇAO, AS A CASE STUDY OF SMALL
ISLAND DEVELOPING STATES**

Richenel Bulbaai

**TOWARD 100% SUSTAINABLE ENERGY
PRODUCTION AND A STRUCTURAL
DECREASE IN ENERGY DEMAND:
CURAÇAO, AS A CASE STUDY OF SMALL
ISLAND DEVELOPING STATES**

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
Prof. Dr. T.T.M. Palstra,
on account of the decision of the Doctorate Board,
to be publicly defended
on Friday the 11th of October 2019 at 10.45 hours

by

Richenel Romualdo Bulbaai

born on the 13th of December, 1967
in Willemstad, Curaçao

This dissertation has been approved by:

Promoter: prof. dr. ir. J.I.M. Halman

Co-promoters: dr. S. Bhochhibhoya, dr.ir. A.G. Entrop

ISBN: 978-94-028-1721-8

DOI number: 10.3990/1.9789036548557

Copyright © 2019 Enschede, The Netherlands.

If one refers to the author, title and year of publication, every part of this thesis may be used for non-commercial purposes, free of charge and free of copy rights without the written permission of the author. For commercial purposes, written permission of the author is required.

Cover picture: Wind turbines in Curaçao, photo by Richenel Bulbaai

Lay out design: Here's Lucy (www.hereslucy.nl)

Printed by: Ipskamp

GRADUATION COMMITTEE:

Chairman/ secretary	prof.dr. G.P.M.R. Dewulf	University of Twente
Promoter	Prof.dr.ir. J.I.M. Halman	University of Twente
Co-promoter	dr. S. Bhochhibhoya dr.ir. A.G. Entrop	University of Twente Saxion Hogeschool
Committee members	Prof.dr. J.Th.A. Bressers Prof.dr.ir. C.H. Venner Prof.dr. A.H.M.E. Reinders Prof.dr.ir. F.A.M. Marchena	University of Twente University of Twente Eindhoven University of Technology University of Curaçao

Summary

The exploitation of fossil fuels is generally considered to be the largest source of global greenhouse gas emissions. Furthermore, fossil fuels are also considered as a finite source of energy. Since the major part of electricity production in the world still comes from fossil fuels, utility companies have necessarily started to focus more on the application of sustainable energy sources. However, replacing fossil fuels by renewable sources such as wind and solar energy comes with some specific challenges. A major issue with regard to solar and wind energy is that energy production is weather dependent. In addition to a season-dependent output level, daily fluctuations in production can also be observed.

Electricity production in Small Island Development States (SIDS¹) remains heavily dependent on imported fossil fuels. In 2009, 98% of the electricity supplied in the Caribbean SIDS was produced from fossil fuels. The problems associated with fluctuating production levels in a transition towards solar and wind energy are particularly relevant for SIDS. Most of these islands have an isolated electricity infrastructure which is not connected to the electricity infrastructure of other countries. As such, they lack the option of cross-border agreements to deal with intermittency. Instead, to guarantee a reliable electricity supply, expensive back-up systems are needed.

The island of Curaçao can be considered as unusual among SIDS in that it already uses significant renewable energy sources. Since the 1980s, Curaçao has built up considerable experience with wind and solar energy. In contrast

¹ SIDS are recognized as a group of small island countries that are characterized by a small internal market, limited resources, and relative high energy and infrastructure costs. SIDS tend to share a vulnerability to climate change and possible natural disasters. The United Nations lists 57 small island developing states. These are broken down into six geographically dispersed regions: the Caribbean; the Atlantic Ocean; the Pacific Ocean; the Indian Ocean; the Mediterranean Sea; and the South China Sea.

to most countries in the world, approximately 34% of the current electricity production in Curaçao is generated by wind and solar energy.

A specific task for the electricity production company in Curaçao will be to replace more than half of its current non-renewable energy plants in the coming decade as they come to the end of their useful life. This necessary replacement can be seen as an opportunity to investigate the possibilities to further increase the renewable energy contribution on the island of Curaçao. This would lead to greater self-sufficiency and a substantial decrease in imported fossil fuels. In addition, a structural decrease in energy demand could also contribute to substantially reducing the use and need for fossil fuels. The aim of this PhD research has been to create a better understanding of the possibilities for SIDS in general, and Curaçao in particular, to realize a significant sustainable energy production and also a structural decrease in energy demand. Consequently, the main research question set and answered in this PhD thesis is:

How to improve energy efficiency in Curaçao and realize a 100% renewable energy production system for Curaçao?

To answer this main research question, the following sub-questions were formulated:

1. What is the current state of Curaçao's electricity infrastructure?
2. What is the status of energy use and energy behavior in the household, the commercial, and the industrial sectors in Curaçao?
3. What are the energy saving options and energy savings potential in the household, the commercial, and the industrial sectors in Curaçao?
4. How to realize a 100% renewable electricity production system for Curaçao?

The findings related to these questions are now summarized.

1. What is the current state of Curaçao's electricity infrastructure?

To gain insight into the current state of Curaçao's electricity infrastructure, a review of relevant literature, documents, and reports, plus in-depth interviews with various staff members of electricity companies and other

stakeholders were conducted. This provided the necessary insights to analyze the specific electricity infrastructure on the island.

The current total installed power capacity in Curaçao is 237.3 MW and consists of three diesel power plants, one gas turbine, two large and some smaller wind farms, and a more limited amount of PV solar systems. The study also identified that Curaçao already has an unusually high proportion of intermittent renewable energy sources (RESs). As in all countries, the electricity power demand in Curaçao depends on the activities of the users and varies accordingly during the day. To match this, electricity production also has to vary. The relatively high, and to an extent uncontrollable, fluctuation in the electricity produced by wind turbines is caused by the changing wind speed, and also the servicing and maintenance requirements. Similarly, with the PV solar production systems, variations in irradiance induce rapid variations in PV electricity production throughout the year. Non-RESs provide the backup for the intermittent RESs. Currently, the electricity infrastructure does not include any grid-scale energy storage systems. A necessary step in reducing or completely eliminating the use of fossil fuels in electricity production in Curaçao will be to investigate the potential use of grid-scale energy storage in the electricity infrastructure to address the intermittent RESs.

2. What is the status of energy use and energy behavior in the household, the commercial, and the industrial sectors in Curaçao?

Two survey studies and two field studies were conducted to investigate energy use and energy behavior in the household sector, the commercial sector, and the industrial sector in Curaçao.

A survey study, in which 384 households in Curaçao participated, provided details about the energy used in various appliances. Currently, energy-efficient appliances are mostly used in high-income households, with take-up considerably lower in middle- and low-income households. Cost savings, rather than environmental concerns, appears to be the main driver in stimulating energy saving behavior. More significantly, it became clear that most households in Curaçao are largely unaware of all the available energy-efficient options that they could adopt to reduce their energy use.

A second survey study, in which 333 representatives of office buildings participated, showed that, contrary to the households, a large majority of

respondents (80%) were aware of, and applied, energy saving options. Again, cost savings rather than environmental concerns appears to be the main driver of energy saving behavior.

A field study investigating the energy use and energy efficiency of 22 hotels in Curaçao revealed a high level of energy awareness. Besides energy-efficient lighting, 50% of the hotels use energy-efficient LED televisions. Notwithstanding this energy awareness, only 59 percent of the hotels have energy-efficient air conditioning units. This leaves plenty of room for energy-efficiency improvements.

In a second field study, the energy use and energy efficiency of nine supermarkets was examined. This field study found that refrigeration (32%) was the highest energy user, followed by air conditioning (27%) and lighting (21%). Furthermore, all the supermarkets in the conducted field study made use of closed freezers (i.e. with doors) which are more efficient than open chest freezers.

3. What are the energy saving options and energy savings potential in the household, the commercial, and the industrial sectors in Curaçao?

In identifying energy saving options and the energy saving potential in the household, commercial, and industrial sectors in Curaçao, this study focused on the savings potential of: reducing standby power losses, adopting passive building design principles, adopting techniques to improve energy efficiency, increasing awareness of energy saving behavior among consumers, and supply-side energy saving possibilities. The overall conclusion was that there was the potential to reduce energy use by 30% compared to the current energy demand.

Based on a field study of 20 households in Curaçao, an assessment was made of standby power losses. It was estimated that about 5% of residential electricity consumption was linked to standby power losses. Options to reduce these losses, besides technical options, include the introduction of import regulations to promote the selling of appliances with lower standby losses and the creation of public awareness through TV and other media campaigns.

Based on an extensive literature review on passive building designs for tropical climates and a field study that included 626 buildings in Curaçao, eight

design principles that could and should be applied for local buildings were identified. A building energy codes program promoted by the government which includes the proposed building design principles could potentially reduce local energy consumption by 11%.

This study also addressed improving supply-side energy performance. It was concluded that this could be improved by: optimizing the baseload since the most efficient electricity sources have to provide power to meet the baseload; running the generators more efficiently to reduce fuel use by approximately 30%; reducing energy losses in the transmission, distribution, and low-voltage infrastructure; and using the waste heat produced by the non-RES generating units which could increase overall efficiency by about 9%.

4. How to realize a 100% renewable electricity production system for Curaçao?

A roadmap has been developed to achieve an energy production system for Curaçao that uses no fossil fuels. The principal steps that need to be taken are:

1. replace the conventional fossil-fuel backups for the RESs with grid-scale energy storage units, by using a kinetic-based energy storage system as developed by Energy-vault;
2. reduce electricity production in line with the estimated potential energy savings;
3. expand the application of solar-based energy to replace the older fossil-fuel generator sets; and
4. use biogas instead of diesel fuel in the remaining generator sets.

The scientific contributions of this PhD research are threefold:

The first contribution is the identification of current energy use in Curaçao and the analysis of the energy saving potential for Curaçao. This identification and analysis has been conducted for both supply-side electricity production as well as demand-side energy use. Curaçao has been taken as a case study, but the approach is generic in the sense that it can also be applied to identify energy use and energy saving potential in other SIDS.

Second, the development of a wide array of options through which Curaçao can not only drastically reduce its demand-side energy use but also the fuel used on the supply side to meet these energy demands. The developed

approach may be considered as generic in the sense that it can also be applied in other SIDS to similarly drastically reduce their energy use.

Third, the development of an approach through which Curaçao and other SIDS can achieve a fully sustainable energy production system based on wind, solar, and biogas as the only energy sources.

The societal contribution of this PhD is:

Curaçao, as part of the Kingdom of the Netherlands, has signed up to the objectives of the Paris Agreement (2015). The findings in this PhD thesis provide clear directions for Curaçao specifically, and for SIDS in general, to meet the objectives of the Paris Agreement ('United Nations Framework Convention on Climate Change', 2015).

Implementation of the findings and suggested approaches included in this PhD thesis will change Curaçao, by 2033, into an island whose electricity plants are based on a fully sustainable energy production system. In addition, implementing the proposed roadmap to achieve a sustainable energy production system in Curaçao will reduce CO₂ emissions by approximately 92%.

Samenvatting

De exploitatie van fossiele brandstoffen wordt algemeen beschouwd als de grootste bron van broeikasgasemissies in de wereld. Daarnaast kampen fossiele brandstoffen met een ander probleem, namelijk dat hun voorraad eindig is. Het grootste deel van de elektrische productie in de wereld komt evenwel nog altijd uit fossiele brandstoffen. Nutsbedrijven zien door deze ontwikkelingen de noodzaak in om zich in de komende jaren meer te gaan concentreren op het toepassen van duurzame energie. Een belangrijk probleem met betrekking tot de inzet van duurzame energiebronnen zoals wind en zon is het feit dat de energieproductie weersafhankelijk is. Als gevolg hiervan vertoont de productie niet alleen een seizoensgebonden productieniveau, maar binnen elk seizoen ook een dagelijks fluctuerend productiepatroon. Deze fluctuaties stelt energieproducenten voor de uitdaging hoe, in geval van een volledig op duurzame energie gebaseerde elektriciteitsproductie, toch een betrouwbare elektriciteitsvoorziening te garanderen.

Ook de elektriciteitsproductie in *Small Island Developing States* (SIDS²) is nog altijd sterk afhankelijk van geïmporteerde fossiele brandstoffen. In 2009 werd 98% van de energie van de eilanden in het Caribisch gebied nog geproduceerd met behulp van fossiele brandstoffen. Het probleem met betrekking tot de fluctuerende energieproductie in geval van de inzet van duurzame energiebronnen zoals wind en zon, geldt in bijzondere mate voor SIDS. Dit vanwege het feit dat het energienetwerk van SIDS niet aangesloten is op het elektriciteitsnetwerk van andere landen. Om toch een betrouwbare elektriciteitsvoorziening te kunnen garanderen, zijn daarom dure back-upsystemen nodig.

Curaçao onderscheidt zich onder de SIDS voor wat betreft het gebruik van duurzame energiebronnen. Al sinds de jaren tachtig heeft Curaçao namelijk

² SIDS: Een door de Verenigde Naties onderscheiden groep van 57 eilanden die vanwege hun kleinschaligheid gekenmerkt worden door niet alleen een kleine, interne economische markt, maar ook door relatief hoge kosten voor energie en infrastructuur. Deze eilanden zijn bijzonder kwetsbaar voor de gevolgen van klimaatverandering en een mogelijke natuurramp. De Verenigde Naties onderscheiden zes geografisch gespreide groepen van SIDS: eilanden in respectievelijk het Caribisch gebied; de Atlantische Oceaan; de Stille Oceaan; de Indische Oceaan; de Middellandse zee; en de Zuid-Chinese Zee.

ervaring opgebouwd met de toepassing van wind- en zonne-energie. Curaçao onderscheidt zich ook wereldwijd voor wat betreft de toepassing van wind- en zonne-energie. In tegenstelling tot verreweg de meeste landen ter wereld, wordt ongeveer 34 procent van de huidige elektriciteitsproductie op Curaçao al opgewekt door gebruik te maken van wind- en zonne-energie.

Een speciale taakstelling in het komende decennium voor het elektriciteitsproductiebedrijf op Curaçao is het vervangen van meer dan 50 procent van zijn huidige, op basis van fossiele brandstoffen draaiende, energiecentrales. Deze noodzakelijke vervanging kan worden aangegrepen om mogelijkheden te onderzoeken hoe de elektriciteitsproductie op Curaçao verder is te verduurzamen. Dit kan leiden tot een substantiële afname van geïmporteerde fossiele brandstoffen. Het eiland zal hiermee op het gebied van zijn energieproductie meer zelfvoorzienend worden. Daarnaast zal bij een structurele afname van het energiegebruik door de afnemende markt, de noodzaak tot de inzet van fossiele brandstoffen voor de energieproductie op het eiland ook afnemen.

Het doel van dit proefschrift is om voor SIDS in het algemeen en Curaçao in het bijzonder, de mogelijkheden te analyseren om enerzijds te komen tot een duurzame energieproductie en daarnaast tot een structurele afname van de energievraag. De hoofdvraag in dit proefschrift is daarom:

Hoe kan de energie-efficiëntie op Curaçao structureel worden verhoogd en kan voor Curaçao een 100% duurzaam energieproductiesysteem worden gerealiseerd?

Teneinde deze hoofdonderzoeksvraag te beantwoorden, zijn de volgende subvragen geformuleerd:

1. Wat is de huidige staat van de elektriciteitsinfrastructuur op Curaçao?
2. Wat is de status van het energieverbruik en het energiegedrag in respectievelijk de huishoudelijke sector, de commerciële sector en de industriële sector op Curaçao?
3. Wat zijn mogelijke energiebesparingsopties en wat is het energiebesparingspotentieel in respectievelijk de huishoudelijke sector, de commerciële sector en de industriële sector op Curaçao?
4. Hoe kan een 100% hernieuwbaar elektriciteitsproductiesysteem worden gerealiseerd voor Curaçao?

Subvraag 1. Wat is de huidige staat van de elektriciteitsinfrastructuur op Curaçao?

Om inzicht te krijgen in de huidige staat van de elektriciteitsinfrastructuur van Curaçao, vonden naast een literatuuronderzoek en het bestuderen van relevante documenten en rapporten, ook diverse diepte-interviews plaats met deskundigen binnen de elektriciteitsbedrijven en met andere stakeholders. Dit leverde de nodige inzichten op om de specifieke elektriciteitsinfrastructuur op het eiland te kunnen analyseren. Het huidige totaal geïnstalleerde vermogen op Curaçao is 237,3 MW. Dit vermogen wordt geproduceerd door één gasturbine, drie dieselcentrales, twee grote en enkele kleine windparken en een kleinschalige energieproductie van PV-panelen. Uit de uitgevoerde analyse werd duidelijk, dat het aandeel aan intermitterende hernieuwbare energiebronnen op Curaçao relatief hoog is. Net als dit het geval is in alle andere landen ter wereld, hangt ook op Curaçao de vraag naar elektriciteit af van het gedrag van de gebruikers en doet er zich gedurende het gehele etmaal een variërende vraag voor naar energie. Ook de elektriciteitsproductie is gedurende de gehele dag niet constant. De relatief hoge fluctuatie in de elektriciteitsproductie wordt bij de windturbines veroorzaakt door de variabele windsnelheid en de noodzakelijke service en het onderhoud aan de windturbines. Bij de PV-productiesystemen, leiden variaties in de mate van zonne-instraling tot fluctuaties in de PV-electriciteitsproductie. De niet-hernieuwbare energiebronnen bieden momenteel nog de back-up voor de intermitterende hernieuwbare energiebronnen. Tot op heden maakt de elektriciteitsinfrastructuur op Curaçao nog geen gebruik van aan het net gekoppelde energieopslagsystemen. Een belangrijke stap die daarom genomen kan worden om de elektriciteitsproductie op Curaçao te verlagen en/ of vrij te maken van fossiele brandstoffen, is door onderzoek te doen naar de mogelijke inzet van aan het net gekoppelde energieopslagsystemen.

Subvraag 2. Wat is de status van het energieverbruik en het energiegedrag in respectievelijk de huishoudelijke sector, de commerciële sector en de industriële sector op Curaçao?

Om de status van het energieverbruik en het energiegedrag op Curaçao in zowel de huishoudelijke sector, de commerciële sector en de industriële sector te onderzoeken, zijn twee enquêtes en een tweetal veldstudies uitgevoerd.

Een enquêteonderzoek waaraan 384 huishoudens op Curaçao hebben deelgenomen, gaf gedetailleerde informatie over het energieverbruik van de

verschillende huishoudelijke apparaten in deze sector. Tot nu toe blijken energiezuinige apparaten meestal gebruikt te worden in huishoudens met een hoog inkomen, terwijl het aandeel energiezuinige apparaten in huishoudens met een laag inkomen en huishoudens met een midden laag inkomen aanzienlijk lager is. Kostenbesparing en niet een bijdrage aan een beter milieu lijken de belangrijkste drijfveren te zijn voor het stimuleren van energiebesparend gedrag. Tevens gaf het resultaat van dit onderzoek ook duidelijk aan dat de meeste huishoudens op Curaçao onvoldoende op de hoogte zijn van alle beschikbare opties waar ze gebruik van kunnen maken, om hun energiekosten te verlagen.

Een tweede enquêteonderzoek waar 333 vertegenwoordigers van kantoorgebouwen aan hebben deelgenomen, maakte duidelijk dat in tegenstelling tot de huishoudens, een grote meerderheid van de respondenten (80 procent) wel op de hoogte is van energiebesparende opties. Deze opties worden ook door hen toegepast. Zoals verwacht, is kostenbesparing de belangrijkste drijfveer voor energiebesparend gedrag in deze sector.

Uit een veldonderzoek waarin het energieverbruik en de energie-efficiëntie van 22 hotels op Curaçao werden onderzocht, werd duidelijk dat in deze sector het niveau van energiebewustzijn hoog is. Naast energiezuinige verlichting gebruikt 50 procent van de hotels energiezuinige ledtelevisies. Ondanks het hoge niveau van energiebewustzijn, blijkt dat slechts 59 procent van de onderzochte hotels op Curaçao beschikt over energiezuinige airconditioners. Dit biedt de mogelijkheid voor een aanzienlijke verbetering van de energie-efficiëntie.

In een tweede veldonderzoek werd het energieverbruik en de energie-efficiëntie van negen supermarkten op het eiland onderzocht. Dit veldonderzoek maakte duidelijk, dat koeling (32%) de grootste energieverbruiker is, gevolgd door airconditioners (27%) en verlichting (21%). Alle supermarkten, die meededen aan dit veldonderzoek maken gebruik van gesloten diepvriezers, die energiezuiniger zijn dan open diepvriezers.

Subvraag 3. Wat zijn mogelijke energiebesparingsopties en wat is het energiebesparings-potentieel in respectievelijk de huishoudelijke sector, de commerciële sector en de industriële sector op Curaçao?

Om mogelijke energiebesparingsopties en het energiebesparingspotentieel in respectievelijk de huishoudelijke sector, de commerciële sector en de industriële sector op Curaçao vast te stellen, concentreerde deze studie zich op het besparingspotentieel van: 1) een vermindering van de energieverliezen

ten gevolge van het sluipverbruik; 2) het adopteren van de principes voor passief bouwen; 3) de toepassing van technieken die de energie-efficiëntie verhogen; 4) het verlagen van het energiegebruik bij afnemers door het bewustzijn bij afnemers te verhogen over de mogelijkheden tot energiebesparing en 5) een analyse van het energiebesparingspotentieel bij de energieleverancier. De algemene conclusie die uit dit onderzoek getrokken kan worden is dat er ten opzichte van de huidige situatie een energiebesparing van 30 procent mogelijk is.

De energieverliezen ten gevolge van het sluipverbruik werden bepaald op basis van een veldonderzoek onder 20 huishoudens op Curaçao. Ongeveer 7,8% van het totale jaarlijkse elektriciteitsverbruik in woningen wordt veroorzaakt door het sluipverbruik. Opties om deze verliezen te verminderen omvatten naast technische opties, de invoering van een importregelgeving ter bevordering van het aanschaffen van apparaten met een laag sluipverbruik. Aanbevolen wordt om via tv en andere mediaprogramma's het publiek bewust te maken van de diverse opties tot het verminderen van het sluipverbruik.

In dit proefschrift worden acht ontwerpprincipes voorgesteld voor het bouwen in de tropen. Deze ontwerpprincipes zijn gebaseerd op een uitgebreide literatuurstudie over passief bouwen in tropische gebieden en een aanvullend veldonderzoek dat 626 gebouwen op Curaçao omvatte. Met een door de overheid via een aanvullend bouwbesluit afgekondigd programma met bouwfysische eisen voor woningen en utiliteitsgebouwen, kan het lokale energieverbruik met 11 procent worden verlaagd.

Deze studie maakt verder duidelijk dat de energie-efficiëntie ook aan de aanbodzijde kan worden verbeterd. Dit kan door: 1) de basislast te optimaliseren, omdat de meest efficiënte elektriciteitsbronnen elektriciteit moeten leveren aan de basislast; 2) verbetering van de efficiëntie van de generatoren, waardoor het brandstofverbruik met ongeveer 30 procent kan worden verminderd; 3) het verminderen van energieverliezen in de transmissie-, distributie- en laagspanningsinfrastructuur en; 4) hergebruik van de warmte, die wordt geproduceerd door de niet-hernieuwbare energiebronnen. Hiermee kan het brandstofverbruik met ongeveer 9 procent worden verminderd.

Subvraag 4. Hoe kan een 100% hernieuwbaar elektriciteitsproductiesysteem worden gerealiseerd voor Curaçao?

In het proefschrift is een stappenplan uitgewerkt om een energieproductiesysteem te realiseren voor Curaçao dat voor 100% vrij is

van het gebruik van fossiele brandstoffen. De belangrijkste stappen die hiertoe moeten worden gezet zijn:

1. het vervangen van de bestaande niet-duurzame back-ups voor zonne- en windenergie door aan het net gekoppelde energieopslagsystemen;
2. het verminderen van de elektriciteitsproductie met de geschatte potentiële energiebesparingen;
3. het vervangen van niet-hernieuwbare energiebronnen door een uitbreiding van de bestaande PV-productiesystemen;
4. de inzet van biogas in plaats van diesel voor de resterende generatorsets en;
5. de inzet van het door Energy-Vault op basis van kinetische energieopslag ontwikkeld systeem als methode voor energieopslag.

De wetenschappelijke bijdragen van dit proefschrift zijn driedelig:

Allereerst, het vaststellen van het huidige energieverbruik op Curaçao en het analyseren van het energiebesparingspotentieel voor Curaçao. Deze vaststelling en analyse zijn uitgevoerd voor zowel de elektriciteitsproductie aan de aanbodzijde als voor het energieverbruik aan de vraagzijde. Curaçao is gebruikt als een case study voorbeeld voor SIDS. De gevolgde aanpak is generiek in die zin dat deze ook kan worden toegepast om het energieverbruik en het energiebesparingspotentieel in andere SIDS te kunnen bepalen.

Ten tweede, de ontwikkeling van een breed scala aan opties, waarmee Curaçao niet alleen haar energieverbruik aan de vraagzijde, maar ook aan de aanbodzijde van energieproductie, drastisch kan verminderen. Ook deze ontwikkelde aanpak kan worden beschouwd als generiek, omdat deze ook kan worden toegepast om het energieverbruik in andere SIDS drastisch te verminderen.

Ten derde, de ontwikkeling van een aanpak voor Curaçao en andere SIDS, om een 100% duurzame energieproductie te kunnen realiseren, die is gebaseerd op wind, zon en biogas, als de enige energiebronnen.

De maatschappelijke bijdrage van dit proefschrift:

Curaçao, als onderdeel van het Koninkrijk der Nederlanden, heeft de doelstellingen van de Overeenkomst van Parijs (2015) mede ondertekend. De bevindingen in dit proefschrift bieden duidelijke aanwijzingen voor SIDS in het

algemeen en voor Curaçao meer in het bijzonder om de doelstellingen van de Overeenkomst van Parijs te halen.

Implementatie van de bevindingen en voorgestelde benaderingen in dit proefschrift, zullen Curaçao in 2033 veranderen in een eiland met een 100% duurzaam energieproductiesysteem. Bovendien zal met de implementatie van het voorgestelde plan om een duurzaam energieproductiesysteem op Curaçao te realiseren, de jaarlijkse CO₂-uitstoot met ongeveer 92 procent worden verminderd.

Resúmen

Generalmente ta konsiderá eksplotashon di kombustibel fósil komo e fuente mayó di emishon di “greenhouse gas”. Ademas, kombustibel fósil ta enfrentá otro problema, esta ku ta trata di un fuente di energia limitá. Teniendo cuenta ku, te ainda, ta produsí gran parti di elektrisidat na mundu usando kombustibel fósil, e kompanianan di utilidat, ku rason, a kuminsá pone mas énfasis riba aplikashon di energia duradero. Sin embargo, sustitushon di kombustibel fósil pa fuente di energia duradero manera energia solar i di bientu ta krea algun desafio spesífiko. Un problema importante pa loke ta trata energia solar i di bientu ta e echo ku produkshon ta dependé di klima. Banda di un produkshon ku ta dependé di temporada di año, tambe por nota un produkshon ku ta fluktua diariamente. E fluktuashon akí ta krea un reto pa produktor di energia, kon pa tòg garantisá un suministro di elektrisidat konfiabel, den kaso di produkshon di elektrisidat ku ta basá kompletamente riba energia duradero. E produkshon di elektrisidat den e Estadonan Insular Chikitu den Desaroyo (EICD)³ tambe ta sigui dependé fuertemente di kombustibel fósil ku ta importá. Na año 2009, ainda 98% di elektrisidat suministrá den e EICD di Karibe a keda produsí usando kombustibel fósil. Problema relatá na produkshon di elektrisidat ku ta fluktua, den kaso di transishon pa yega na energia duradero, manera di solo i bientu ta konta en partikular pa EICD. Esaki ta debí na e echo ku infrastruktura di elektrisidat di e islanan akí ta isolá, nan no ta konektá ku infrastruktura di elektrisidat di otro pais. Pa garantisá un suministro di elektrisidat konfiabel, kompania di utilidat tin mester di sistema di respaldo karu.

Por konsiderá e isla Kòrsou un eksepsion kompará ku otro pais di EICD, komo Kòrsou ta produsí su elektrisidat pa gran parti usando un kantidat

³ EICD (SIDS, Small Island Developing States) ta un grupo di 57 isla ku Nashonnan Uni ta distinguí a base di nan tamaño chikitu i ku ta keda tipifiká, no solamente pa un merkado chikitu ekonómiko interno, sino tambe pa kosto relativamente altu di energia i di infrastruktura. E islanan akí partikularmente ta vulnerabel pa konsekuensia di kambio di klima i posibel desaster natural. Nashonnan Uni ta hasi distinshon entre seis grupo di EICD partí den área geográfiko ku respektivamente isla den: Karibe, Oséano Atlántiko, Oséano Pasífiko, Oséano Indio, Laman Mediteráneo i Laman Sur di China.

respetá di energia duradero. For di dékada ochenta, Kòrsou a akumulá hopi eksperensia riba e tereno di energia di bientu i solar. Kontrali na mayoria pais na mundu, aproksimadamente 34% di produkshon aktual di elektrisidat na Kòrsou ya ta keda generá mediante di uso di energia di solo i bientu.

Un tarea spesífiko pa e kompania di produkshon di elektrisidat na Kòrsou ta pa remplasá mas ku 50% di su plantanan aktual di elektrisidat ku ta funshoná ku kombustibel fósil, den e próksimo dékada. Por mira e kambio nesesario akí komo un oportunidat pa investigá e posibilidatnan pa oumentá produkshon di elektrisidat na Kòrsou mas tantu ainda pa medio di energia duradero. Esaki por kondusí na un bahada supstansial di importashon di kombustibel fósil. Lokual ta hasi e isla mas outosufisiente loke ta trata produkshon di energia. Ademas, un bahada struktural di e demanda di energia, lo kontribuí tambe na redukshon supstansial di nesesidat pa uso di kombustibel fósil pa produkshon di energia riba e isla.

Meta di e tésis doktoral akí ta pa analisá e posibilidatnan den e paisnan EICD en general i na Kòrsou en partikular pa realisá un produkshon di energia duradero di un banda i di otro banda un bahada struktural di e demanda di energia. Konsekuwentemente, e pregunta prinsipal di e investigashon den e disertashon akí ta:

Kon por mehorá efisiensia energétiko struktural na Kòrsou i realisá un sistema di produkshon di elektrisidat 100% duradero?

Pa kontestá e pregunta prinsipal di e investigashon akí, a fórmula e siguiente suppreguntanan:

1. Kon e situashon aktual di infrastruktura di elektrisidat na Kòrsou ta?
2. Kua ta e status di uso di energia i komportashon energétiko den e sektornan respektivamente doméstiko, komersial i industrial na Kòrsou?
3. Kua ta e opshonnan ku tin pa spar energia i kua ta e potensial pa spar energia den e sektornan respektivamente doméstiko, komersial i industrial na Kòrsou?
4. Kon por realisá un sistema di produkshon di elektrisidat ku ta 100% duradero na Kòrsou?

Hasiendo uso di e kuater suppreguntanan akí, por resumé resultado di e investigashon di siguiente manera.

Suppregunta 1) Kon e situashon aktual di e infrastruktura di elektrisidat na Kòrsou ta?

Pa optené informashon di e status aktual di infrastruktura eléktriko na Kòrsou, a hasi estudio di literatura, dokumento i di rapòrt relevante. Banda di esei a realisá vários entrevista den profundidat ku ehekutivo i eksperto di e kompania di utilidat na Kòrsou i ku otro persona di interes. Tur esaki a resultá den dato i konosementu nesesario pa analisá e infrastruktura di elektrisidat spesífiko di e isla.

Aktualmente e kapasidat total di produkshon di elektrisidat na Kòrsou ta 273.3 MW. Ta realisá e kapasidat akí ku un turbina di gas, tres planta di diesel, dos parke di mulina di biento grandi, algun chikitu i un kantidat di panel solar i tambe produkshon di energia solar na eskala chikí di sistema solar PV (fotovoltaíko). For di análisis realisá den e estudio akí a sali na kla, ku e proporshon di fuente di energia renovabel intermitente na Kòrsou ta relativamente altu. Manera na tur pais na mundu e demanda di energia eléktriko na Kòrsou ta dependé di e aktividatnan di e konsumidónan i konsekuentemente ta varia durante bintikuater ora. Esaki ta trese kuné ku produkshon di elektrisidat durante di dia tambe no ta konstante.

E fluktuashon relativamente altu den produkshon di elektrisidat pa medio di e mulinanan di biento ta konsekuensia di e velosidat di biento ku ta varia i tambe di servisio i mantenementu nesesario na e turbinanan di biento. Meskos ta konta pa e sistema di produkshon solar PV, kaminda variashon den grado di radiashon solar ta kondusí na fluktuashon rápido den produkshon di koriente di panel solar.

E fuentenan di energia konvenshonal ta fungi te na e momentu akí, komo respaldo pa e fuentenan di energia duradero intermitente. Aktualmente e infrastruktura eléktriko na Kòrsou ainda no ta usa ningun sistema ku por almasená energia konektá na e ret di elektrisidat. Pa e motibu ei un paso importante ku por tuma pa redusí produkshon di elektrisidat i, òf eliminá produkshon di elektrisidat na Kòrsou por kompleto di kombustibel fósil, ta pa investigá e posibel uso di sistema di almasenamentu di energia konektá na ret di e infrastruktura eléktriko.

Suppregunta 2) Kua ta e status di uso di energia i komportashon energétiko den e sektornan respektivamente doméstiko, komersial i industrial na Kòrsou

Pa investigá status di uso di energia i komportamentu energétiko den e sektornan doméstiko, komersial i industrial na Kòrsou a realisá dos enkuesta i dos estudio den bèlt.

Un enkuesta kaminda 384 kas na Kòrsou a partisipá, a suministrá informashon detayá di uso di energia di diferente aparato doméstiko den e sektor akí. Ta resultá ku na e momento akí, den e kasnan kaminda entrada finansiero ta haltu, ta usa prinsipalmente aparato doméstiko ku ta konsumí poko energia, miéntras ku na kas kaminda tin entrada abou i entrada medio abou e proporshon di aparato di konsumo di energia abou ta konsiderablemente ménos. Sparmentu di gastu i no preokupashon ambiental ta parse di ta e motibu mas importante, pa stimulá komportashon pa ekonomisá riba energia. Resultado di e estudio akí ta indiká tambe klaramente ku mayoría parti di kas na Kòrsou no ta sufisientemente konsiente di tur e opshonnan disponibel ku por apliká pa redusí gastu di energia.

Un di dos enkuesta, kaminda 333 representante di edifisio di ofisina a partisipá, ta mostra klaramente ku, kontrali na e sektor doméstiko, un gran mayoría di e informantenan (80%) konosé i ta apliká e diferente opshonnan pa spar energia. Manera a spera, den e sektor akí tambe sparmentu di gastu ta parse di ta e motor prinsipal pa komportashon pa ekonomisá riba energia en bes di preokupashon ambiental.

Un estudio den bèlt ku a investigá e konsumo di energia i tambe e efisiensia energétiko na 22 hotèl na Kòrsou, a demonstrá ku den e sektor akí e nivel di konsenshi energétiko ta altu. Banda di iluminashon di konsumo abou, 50% di hotèl ta usa televishon LED di konsumo abou. Apesar di e konsenshi energétiko akí, solamente 59% di hotèl tin unidatnan di èrko di konsumo abou. Esaki ta ofresé un oportunidat pa mehoransa signifikativo di efisiensia energétiko.

Un di dos investigashon den bèlt a studia uso di energia i efisiensia energétiko di nuebe supermerkadu. E estudio akí a deskubrí ku refrigerashon (32%) ta loke ta gasta mas energia, sigui pa èrko (27%) i iluminashon (21%) den e sektor akí. Tur supermerkadu ku a partisipá den e estudio den bèlt akí ta hasi uso di frizer será (ku porta), ku ta mas eficiente energétikamente ku frizer habrí.

Suppregunta 3) Kua ta e opshonnan ku tin pa spar energia i kua ta e potensial pa spar energia den e sektornan respektivamente doméstiko, komersial i industrial na Kòrsou

Pa determiná e posibel opshonnan pa spar energia i e potensial pa spar energia, respektivamente den e sektor doméstiko, sektor komersial i sektor industrial na Kòrsou, e estudio akí a pone énfasis riba e potensial pa ekonomisá pa medio di: 1) redukshon di pèrdida di energia di aparato ku ta para pendiente; 2) adopshon di prinsipio di diseño pa konstrukshon pasivo di edifisio; 3) aplikashon di téknika pa mehora efisiensia energétiko; 4) oumento di konsiensia energétiko bou di e konsumidónan i 5) análisis di e potensial pa redukshon energétiko na banda di e suministradó di energia. E konklushon general ku por saka for di e estudio akí ta, ku ta eksistí e posibilidat pa redusí uso di energia ku mas òf ménos 30%, kompará ku e demanda energétiko aktual.

Basá riba un estudio di vèlt kaminda 20 kas na Kòrsou a partisipá, a realisá un evaluashon di pèrdida di energia di aparato ku ta para pendiente, esta standby. Alrededor 5% di e konsumo total anual di energia den vivienda ta keda kousá pa aparato ku ta para pendiente.

E opshonnan pa redusí pèrdida energétiko ta inkluí, banda di e opshonnan tékniko, tambe introdukshon di regulashon di importashon pa promové kompra di aparato di konsumo di elektrisidat abou. Ta rekomendá pa via televishon i otro medio konsientisá públiko di diferente alternativa pa redusí pèrdida di energia di aparato ku ta para pendiente.

Den e disertashon akí ta proponé ocho prinsipio di diseño pa konstruí den klima tropikal. E prinsipionan di diseño akí tin nan base den un revishon di literatura ekstenso riba konstrukshon pasivo den área tropikal i un estudio den vèlt adishonal ku a inkluí 626 edifisio na Kòrsou. Ku un programa ku kódigo di efisiensia energétiko pa edifisio, proklamá pa gobièrnu, pa medio di un dekreto di konstrukshon komplementario, ku eksigensia físiko, pa kas i edifisio pa servisio públiko, lo por redusí konsumo di energia lokal ku 11%. Ku un programa ku kódigo di efisiensia energétiko pa edifisio, proklamá pa gobièrnu, pa medio di un dekreto di konstrukshon komplementario, ku eksigensia físiko, pa kas i edifisio pa servisio públiko, lo por redusí konsumo di energia lokal ku 11%.

E estudio akí a mostra ademas ku por mehorá efisiensia energétiko na banda di e produktornan di elektrisidat tambe. Por logra esaki mediante: 1)

optimalisashon di e produkshon básiko di elektrisidat, ya ku e fuentenan di elektrisidat mas efisiente tin ku suministrá elektrisidat na e produkshon básiko; 2) oumento di efisiensia di e generator-nan, loke por redusí konsumo di kombustibel ku aproksimadamente 30%; 3) redukshon di pèrdida di energia den infrastruktura di transmishon, distribushon i vòltahe abou i 4) reutilisashon di e kalor produsí pa e fuentenan di energia konvenshonal, lokual por redusí konsumo di kombustibel ku aproksimadamente 9%.

Suppregunta 4) Kon por realisá un sistema di produkshon di elektrisidat ku ta 100% duradero na Kòrsou?

Den e disertashon akí a diseñá un plan di instrukshon paso pa paso pa realisá un sistema di produkshon di energia pa Kòrsou ku ta 100% liber di uso di kombustibel fósil. E pasonan mas importante ku tin ku tuma ta:

1. remplasá sistema di koriente konvenshonal eksistente, ku ta forma back-up pa energia solar di bientu, pa unidat di almasená energia, konektá na ret;
2. redusí e produkshon di elektrisidat conforme e redukshon potensial di energia kalkulá;
3. remplasá e fuentenan di energia no-renovabel ku un ampliashon di e sistema di produkshon fotovoltáiko eksistente.
4. hasi uso di biogas na lugá di diesel pa e unidatnan di produkshon konvenshonal ku a sobra.
5. hasi uso di e sistema desaroyá pa Energy-Vault riba base di almasenamentu di energía kinétiko komo método pa warda energia.

Kontribushon sientífiko di e disertashon akí ta tripel:

Na promé lugá determinashon di e konsumo aktual di energia na Kòrsou i análisis di e potensial pa spar energia na Kòrsou. A realisá e evaluashon i análisis akí tantu pa produkshon di elektrisidat na banda di oferta komo pa konsumo di energia na banda di demanda. A usa Kòrsou komo un ehèmpel pa un kaso di estudio pa EICD. Sin embargo e aserkamentu apliká ta genérico, den sentido ku por aplik'é tambe pa determiná konsumo di energia i e potensial pa redukshon di energia na otro isla di EICD.

Na di dos lugá desaroyo di un gama amplio di opshon ku kua Kòrsou, no solamente por redusí su konsumo di energia drástikamente no solamente na banda di demanda, sino tambe na banda di oferta di produkshon di energia. E prosedimentu desaroyá akí tambe por konsiderá genérico, komo ku por us'é tambe pa redusí konsumo di energia na e otro paisnan di EICD drástikamente.

Na di tres lugá desaroyo di un prosedimentu pa Kòrsou i otro pais EICD pa por realisá un sistema pa produkshon di energia 100% sostenibel basá riba bientu, solo i biogas komo e úniko fuentenan di energia.

Kontribushon di e disertashon akí na komunidad:

Kòrsou komo parti di Reino Hulandes, di mes, konhuntamente a firma e metanan di e Akuerdo di Paris (2015). E resultadonan di e tésis doktoral akí ta ofresé indikashon evidente pa e paisnan di EICD en general i pa Kòrsou en partikular pa logra e metanan di e Akuerdo di Paris.

Implementashon di e resultadonan i prosedimentu ku ta proponé den e tésis doktoral akí, lo konvertí Kòrsou, den un isla ku un sistema di produkshon di energia 100% sostenibel na 2033. Ademas, implementashon di e plan proponé pa realisá un sistema di produkshon di energia sostenibel na Kòrsou, lo redusí emishon anual di CO₂ ku aproksimadamente 92%.

Table of Contents

Summary	i
Samenvatting	vii
Resúmen	xiv
Table of Contents.....	xxi

CHAPTER I

General introduction	I
1.1 Background of this research	I
1.2 Problem statement.....	4
1.3 Curaçao as a Caribbean small island developing state.....	8
1.4 Research objectives.....	9
1.5 Research questions.....	9
1.6 Outline of the thesis	10

CHAPTER 2

The electricity infrastructure in Curaçao	15
2.1 Introduction	15
2.2 A short history of Curaçao's electricity infrastructure.....	15

2.3.2 Electricity demand in Curaçao	18
2.4 Curaçao's electricity production	23
2.4.1 Non-renewable sources.....	23
2.4.2 Renewable energy sources in Curaçao.....	24
2.5 Concluding remarks on Curaçao's electricity infrastructure.....	32
 CHAPTER 3	
Examining energy use and energy behavior in Curaçao	37
3.1 Introduction to international developments in energy use	38
3.2 Factors that influence household energy use.....	38
3.3 Household characteristics in Curaçao.....	40
3.4 Household energy use survey in Curaçao: Research approach	42
3.5 Household energy use survey in Curaçao: Results and analysis.....	43
3.5.1 Number of dwellings per household size and per income category in Curaçao energy survey	44
3.5.2 Household sector energy behavior in Curaçao	45
3.5.3 Electricity consumption by type of appliance and income level by households in Curaçao.....	48
3.6 Energy use in office buildings in Curaçao.....	51
3.6.1 A survey about energy use in office buildings in Curaçao: Research approach	52

3.6.2 A survey about energy use in office buildings in Curaçao: Results and analysis.....	53
3.6.3 Awareness of the importance of saving energy in office buildings.....	58
3.7 Introduction to energy use in hotel buildings in Curaçao	59
3.7.1 Energy use by hotels in Curaçao: Research approach	60
3.7.2 Survey results and analysis	61
3.8 Energy use by supermarkets in Curaçao.....	65
3.8.1 Energy use by supermarkets in Curaçao: Research approach	66
3.8.2 Energy use by supermarkets in Curaçao: Results and analysis.....	66
3.9 Conclusions from examination of energy use and energy behavior in Curaçao	68

CHAPTER 4

Energy saving opportunities in Curaçao	73
4.1 The impact of standby power consumption.....	74
4.1.1 Introduction to standby power and standby power losses	74
4.1.2 Research approach to measure standby power losses in Curaçao	78
4.1.3 Key findings from the measurements of standby power losses in Curaçao	82
4.1.4 Opportunities to reduce standby power consumption in Curaçao	86

4.1.5 Conclusions: standby power losses in Curaçao	88
4.2 Energy-efficient building designs for a tropical climate	88
4.2.1 Key tropical building design principles	89
4.2.2 A field study of the application of passive design principles in Curaçao: research approach.....	107
4.2.3 A field study on the application of passive design principles in Curaçao: results and analysis.....	108
4.3 Techniques for improving the energy efficiency of the most- commonly used appliances	116
4.3.1 Improving the energy efficiency of lighting systems	116
4.3.2 Improving energy efficiency of refrigerators.....	120
4.3.3 Improving energy efficiency of washing machines	121
4.3.4 Improving energy efficiency of air conditioners.....	121
4.3.5 Improving energy efficiency of office appliances.....	124
4.4 A global estimation of the energy savings potential in Curaçao.....	125
4.5 Conclusions on energy savings options and energy saving potential for Curaçao	132

CHAPTER 5

Towards 100% renewable energy production 137

5.1 The process steps to enhance the sustainability level of the electrical power production in Curaçao.....	137
---	-----

5.2	Opportunities to enhance the sustainability of electrical power production in Curaçao.....	145
5.3	Making electricity production in Curaçao free from fossil fuels	149
5.4	Conclusions on improving supply-side sustainability.....	161

CHAPTER 6

Discussion, conclusions, and recommendations	165
6.1 Summary of results and general discussion	165
6.1.1 The current state of Curaçao's electricity infrastructure	165
6.1.2 The current energy use and energy behavior in Curaçao.....	166
6.1.3 Energy saving options and energy saving potential in Curaçao..	168
6.1.4 Towards a 100% renewable electricity production system in Curaçao	170
6.2. Scientific contributions	172
6.3. Societal relevance.....	173
6.4 Limitations.....	173
6.5 Recommendations	174

References	180
Abbreviations	197
Appendix 1: Small wind turbines in Curaçao	198
Appendix 2: Survey questions energy use by households in Curaçao	199
Appendix 3: Survey questions energy use by office buildings in Curaçao	200
Appendix 4: Results energy use by supermarkets in Curaçao	201
Appendix 5: Results energy use by supermarkets in Curaçao	202
Appendix 6: Survey questions to measure standby power losses in Curaçao	203
Appendix 7a: Energy savings potential.....	204
Appendix 7b (continued): Energy savings potential	205
Appendix 7c (continued): Energy savings potential.....	206
Appendix 8: Expected electricity demand in Curaçao (2014- 2033)	207
Acknowledgement	208
About the author	210

CHAPTER I

General introduction

In this opening chapter, the research background, the problem statement, a description of Curaçao, a Caribbean Small Island Developing State (SIDS), the research objectives, the research questions answered through the conducted research, the expected scientific contribution and the societal relevance, and the outline of the thesis are described.

1.1 Background of this research

As far back as 1713, the German forester and scientist, Carl Von Carlowitz, used the term “nachhaltigkeit” (sustainability) in the subtitle of his book *Sylvicultura Oeconomica*. Since then, English and French foresters chose the practice of planting trees as a path to ‘sustained-yield forestry’ (Heinberg, 2010; Kuhlman & Farrington, 2010). However, it was not until after 1987 that sustainability received worldwide attention with the publication *Our Common Future*, widely referred to as the Brundtland Report, by the World Commission on Environment and Development. This commission, chaired by Gro Harlem Brundtland, and its report defined sustainability as “the kind of development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). In recent years, many alternative definitions of the term sustainability have been introduced, and various interpretations exist (Pope, Annandale, & Morrison-Saunders, 2004). Despite these many definitions of sustainability, Dr Brundtland’s definition is still widely recognized and used in many studies, as is the case in this PhD thesis.

Sustainable development has become an important objective for policymakers in organizations (Singh, Murty, Gupta, & Dikshit, 2009). Many governments, industries, and organizations are trying to adapt their actions and behavior in order to improve the ability of future generations to meet their own needs (Entrop, 2013).

Numerous governments, industries, and organizations instigate actions aimed at sustainable development through the integration of economic prosperity, environmental quality, and social consistency (Böhringer & Jochem, 2007). In this, these organizations look for models, tools, and metrics to assess the extent to which, and the ways in which, their activities are sustainable when taking economic, environmental, and social aspects into account (Singh et al., 2009).

Singh et al. (2009) provide several examples of sustainability assessment tools such as the:

1. *Global reporting initiative framework*, designed to raise the quality, service, and accuracy of sustainability reporting. This framework was introduced by the United Nations Environment Programme (UNEP), in cooperation with United States' non-government organizations and the Coalition for Environmentally Responsible Economics (ERES). The focus is on social, environmental, and economic aspects;
2. *Hierarchical framework*, consisting of 15 main themes divided into 38 subthemes, developed by the United Nations Commission of Sustainable Development (CSD) with the objective of evaluating governmental advancement towards sustainable development goals. The themes are split into the following four areas: social, environmental, economic, and institutional;
3. *Sustainability indicator framework*, developed in 2002 by the Institution of Chemical Engineers to measure the sustainability level of operations within industrial processes. This framework focuses on environmental, economic, and social areas.

The exploitation of fossil fuels is generally considered to be the largest source of global greenhouse gas emissions ("The International Energy Agency IEA", 2015). Moreover, fossil fuels are also considered to be a finite source of energy. Since most electrical production in the world still uses fossil fuels, utility companies have necessarily started to increasingly concentrate on the application of sustainable practices.

To cope with these environmental challenges, the United Nations Framework Convention on Climate Change (UNFCCC) parties signed, on 12 December 2015, a landmark agreement in Paris, also known as the 'Paris agreement'. This agreement addresses the reduction of greenhouse gasses (GHG) emissions and the acceleration and reinforcement of the actions and the investments required for a sustainable low carbon future. The main objective of this agreement is to keep the global temperature rise in this century to well below 2 °C above the pre-industrial level; as well as to limit global temperatures to 1.5 °C above pre-industrial levels. In addition, this agreement will reinforce the global response to mitigate the negative risks and effects of climate change (United Nations Framework Convention on Climate Change, 2015). In December 2018, the 24th International Climate Change Conference took place in Katowice, Poland, where 200 nations agreed to put the 2015 Paris agreement into practice.

The United Nations Conference on Environment and Development (UNCED) that was held in Rio de Janeiro, Brazil between 3-14 June 1992 (also known as the "Earth Summit" or the "Rio Conference") recognized Small Island Developing States (SIDS) as a distinct group of developing countries (Timilsina & Shah, 2016). SIDS tend to face similar constraints in their sustainable development efforts such as a narrow resource base depriving them of the benefits of economies of scale; small domestic markets and heavy dependence on a few external and remote markets; high energy, infrastructure, transportation, communication, and servicing costs; little resilience to natural disasters; high volatility in economic growth; limited opportunities for the private sector, and a proportionately large reliance of their economies on their public sector. SIDS are also facing environmental vulnerabilities (UN-OHRLLS, 2011). They are seen as among the most vulnerable countries to climate change, especially to rising sea levels. Further, they have relatively small watersheds threatening fresh water supplies; fragile island ecosystems with their renowned biological diversity among the most threatened in the world (UNEP et al., 2012). With a few exceptions (e.g. Trinidad and Tobago, Papua New Guinea, Timor-Leste), SIDS have very limited fossil fuel resources. As a consequence, they widely recognize the need to move towards low-

carbon, climate-resilient economies. Renewable technologies have the advantage of providing energy at a lower cost than fossil fuels and making SIDS more sustainable.

During the 1992 Rio Conference, the Caribbean islands were identified as one of the SIDS regions. In April 1994, the first “Global Conference on Sustainable Development of SIDS” in Barbados, adopted the “Barbados Programme of Action” (UN, 1994). This program was updated a decade later in the “Mauritius Strategy” (UN, 2005; Kelman, & West, 2009). More recently, an international framework known as the “Modalities of Action Pathway”, or the “Samoa Pathway”, was developed. This framework was a product of the third International conference on SIDS. This conference, (called “The sustainable development of Small Island Developing States through genuine and durable partnerships”) was held in the period of 1-4 September 2014 in Apia, Samoa (UN, 2014). The Samoa Pathway addresses several subjects such as sustainable transportation, ocean and seas, disaster risk reduction, climate change, sustainable energy, and food security and nutrition. The general lack of information related to energy in SIDS, such as energy production, energy use, energy behavior and sustainability, is a major obstacle to the successful implementation of sustainable energy. For this reason, a high priority is given in SIDS to conducting research on energy efficiency and sustainability of electricity production.

1.2 Problem statement

Electricity production in SIDS is strongly dependent on imported fossil fuels ("Division for Sustainable Development", 2013; Weisser, 2004; Niles & Lloyd, 2014). In 2009, 98% of the energy demand in the Caribbean SIDS was met by fossil fuels (Niles & Lloyd, 2014). However, many utility companies are now attempting to make their electricity production more sustainable by replacing conventional energy sources with renewable energy sources (RESs). The main issue with regard to RESs is that most of them are weather dependent and display daily and/or seasonal variations. Researchers have demonstrated that this will result in limitations to the installed capacity of RESs (Duic, Alves,

Chen, & Da Graça Carvalho, 2003; Duić & Da Graça Carvalho, 2004). This limitation is particularly severe in SIDS because most of them have a small, isolated electricity infrastructure (van Alphen, Hekkert, & van Sark, 2008; Weisser, 2004). The main challenge of an isolated electricity infrastructure not connected to the electricity infrastructures of other countries is that the electricity supply is dependent on expensive back-up systems to guarantee a reliable electricity supply. In addition, intermittent electricity sources such as wind and solar energy exhibit uncontrolled variations in outputs. For this reason, back-up systems are even more necessary to supplement these intermittent sources. Furthermore, there are other barriers that impede the implementation of RESs in SIDS, such as (Niles & Lloyd, 2014; Weisser, 2004):

1. limited financial resources;
2. lack of awareness of RES alternatives;
3. lack of technical knowledge on RESs;
4. insufficient human capacity; and
5. high renewable energy costs.

Other barriers that slow the implementation of RESs in SIDS are that RESs require large parcels of lands, and intermittent RESs require additional financial investments due to the need for back-up. In addition, a lack of technical knowledge impedes the ability to exploit and manage RES technologies. Consequently, these barriers lead to ill-informed decision-making and deficient policy design.

Further, as Niles and Lloyd (2014) have argued, in many SIDS, the lack of awareness and education; lack of information; lack of appropriate policies; and unwillingness by consumers and energy suppliers to invest in energy-efficiency technologies restrict the potential considerable reduction in energy use. In addition, the high cost of energy-efficient options is also a major barrier to realizing energy efficiency gains in SIDS.

Apart from these barriers to reform, utility companies in SIDS face many other challenges and key among them is guaranteeing a reliable electricity supply. Since RESs are not continuously available, non-

dispatchable, and most SIDS have no dedicated energy storage at present, intermittent RESs cannot simply replace fossil fuel sources. Balancing energy supply and energy demand is required to guarantee energy reliability. Therefore, in an ideal scenario, to guarantee 100% energy supply in SIDS, each 1 kWh produced by intermittent RESs must be backed up by a conventional, dispatchable energy source if energy storage is not available. A dispatchable energy source is one that can be controlled by electricity plant operators according to the electricity demand. Fossil-fuel-based conventional electricity back-up, consequently, negatively affects the sustainability of electricity production. To date, sustainability studies tend not to incorporate the effect of this type of backup in their sustainability assessments.

According to Lund and Mathiesen (2009), there are three main technological options to improve the energy sustainability of a society: energy savings on the demand side, energy efficiency improvements on the supply side, and the replacement of non-RESs with several renewable energy sources. These three technological options are in line with the three-way strategy of the Trias Energetica model (www.Eurima.org, 2018; Entrop, 2013). This illustration is in Figure 1.1, with the three strategies being:

1. first, reduce energy use through energy efficiency measures;
2. use RESs, such as wind and solar energy, where possible; and
3. where energy production from RESs is not possible, use conventional energy sources as efficiently as possible.

Figure 1.1: Trias Energetica model (Eurima, 2018)

Electricity production in SIDS is largely based on fossil fuels. Despite fossil fuels polluting the environment and their supply being limited and will eventually run out, many SIDS' governments still promote energy from fossil-fuel sources. Consequently, the potential of renewable-energy and energy efficiency technology in SIDS is still hardly investigated. This results in a lack of technical knowledge on how to realize sustainable energy production in SIDS. Furthermore, the lack of awareness and information on how to reduce energy use restricts the potentially significant reduction in energy use.

For these reasons, this study will focus on sustainable electricity production and energy use reduction in SIDS. The study will be based on the three-way strategy of the Trias Energetica model (Chapters 3, 4, and 5). The proposed design will involve at least three major technological changes: energy savings on the demand side; efficiency improvements in the energy production; and the replacement of fossil fuels by various sources of renewable energy (Lund & Mathiesen, 2009). Curaçao as a representative Caribbean small island developing state, will be taken as a case study for this research.

1.3 Curaçao as a Caribbean small island developing state

The country of Curaçao is an Antillean island in the Southern Caribbean Sea, about 65 km north of the Venezuelan coast. Curaçao has a population of just over 150,000 in an area of 444 km² (CBS, 2011). The island extends from 68 to 70 degrees west of the Greenwich meridian and from 12 to 13 degrees north of the equator. Curaçao is located in the southern Caribbean dry zone, and it is characterized by a semi-arid to arid climate, with distinct dry and rainy seasons. The rainy season is from September until January and the dry period from February through June, with July and August referred to as the transitional months. Curaçao has warm tropical temperatures, with the highest mean temperatures in September. The average temperature is 27.9°C, the average temperature of the seawater is 27°C (Meteo Curaçao, 2016), and the winds blow predominantly from the east and throughout the year. Given the favorable climatic conditions in Curaçao, renewable energy technologies may have a substantial potential.

Indeed, since the 1980s, Curaçao has built up experience with the application of renewable energy in the form of wind and solar energy. Approximately 34% of the current electricity production in Curaçao is already generated by wind and solar energy. Furthermore, Curaçao has the ambition to further increase its electricity production from renewable energy sources in the near future. This will lead to greater self-sufficiency, a decrease in imported fossil fuels, and the growth of economic activities, such as new companies willing to sell, install, and maintain RESs. In addition, more than half of all the non-renewable electricity plants will have to be replaced in near future (HEN, 2014). As a result, the need to explore new renewable technologies becomes ever more important. Despite the mentioned ambition and expected advantages, there are limitations to the further development and implementation of new renewable technologies in Curaçao such as a lack of knowledge about appropriate technologies to realize fully sustainable energy production and to support effective adaptations to climate change (*'Strategies for sustainable long term economic development in Curaçao'*, 2013).

1.4 Research objectives

The objective of this PhD thesis is to create a better understanding of the possibilities for SIDS to achieve sustainable energy production and also a structural decrease in energy demand.

The objectives *within* this PhD research project are to:

- Examine current energy production and energy use on the island of Curaçao;
- Analyze the options to improve energy efficiency on both the supply and the demand sides and to design a 100% renewable energy production system.

1.5 Research questions

The objectives of this study underpin the main research question:

How to improve energy efficiency in Curaçao and realize a 100% renewable energy production system for Curaçao?

To answer the main research question, the following four research sub-questions will be answered:

Question 1: *What is the current state of Curaçao's electricity infrastructure?*

To answer the first sub-question, a review of relevant literature, documents, and reports, and in-depth interviews with various staff members of electricity companies and other stakeholders will be conducted. This will provide the necessary insights to analyze the specific electricity infrastructure on the island.

Question 2: *What is the status of energy use and energy behavior in the household, the commercial, and the industrial sectors in Curaçao?*

To gain insights into energy use, and characteristics that influence energy use and energy behaviors in Curaçao, a review of relevant literature, documents, and reports will be conducted. In addition, surveys in the household sector, the commercial sector, and the industrial sector will be conducted. Here, the aim is to better understand energy use and energy behavior in Curaçao. The results from the literature review and the surveys will identify challenges to improving energy efficiency in Curaçao.

Question 3: What are the energy-saving options and energy savings potential in the household, the commercial, and the industrial sectors in Curaçao?

There are potentially many options to improve energy efficiency in Curaçao. To obtain insights into energy-saving options and the energy savings potential in Curaçao, an extensive study will be conducted on the impact of standby power consumption; on potential energy savings through the application of passive building design principles; and on techniques to improve the energy efficiency of the most-used appliances such as lighting systems, refrigerators, washing machines, air conditioners, and office appliances.

Question 4: How to realize a 100% renewable electricity production system for Curaçao?

A production system will be designed on the basis of an extensive literature review on available renewable electricity production options and the specific requirements given the Curaçao context.

1.6 Outline of the thesis

The outline of this thesis is presented in Figure 1.2.

Chapter 2 describes the current state of the electricity infrastructure of Curaçao; the electricity network, its components, and electricity production and demand.

Chapter 3 elaborates on the current state of energy use, and energy behavior, in several sectors in Curaçao. Although several studies have been conducted on energy behavior and energy use worldwide, no literature is available specifically with regard to Curaçao. To provide insights into how the residents, the commercial sector, and the industrial sector of Curaçao use energy, four surveys were conducted in the household, office buildings, hotel, and supermarket sectors. This chapter elaborates on the results of these surveys.

Chapter 4 discusses different energy savings opportunities such as standby power, energy-efficient buildings for a tropical climate, and technological challenges for lighting systems and other appliances. In addition, this study identifies the highest energy-consuming appliances as well as the energy savings potential for these appliances.

Chapter 5 provides insight into how the electricity supply could be made more sustainable. This chapter focuses on the supply-side energy-efficiency opportunities and the potential diversification of electrical power plants. Following this, the chapter presents several steps that have already been taken towards making electricity production in Curaçao free from fossil fuels.

Finally, Chapter 6 presents the discussion, conclusions, and recommendations. The conclusions answer the main research question. Thereafter, the scientific contributions, societal relevance, and limitations of this research are discussed. In the final section of this chapter, various recommendations are offered that could be useful for the government, residents, industries, and electricity companies to improve energy efficiency and make the society more sustainable.

Figure 1.2: Outline of the chapters and research questions leading to fulfill the research objective

CHAPTER 2

The electricity infrastructure in Curaçao

This chapter provides an answer to the first research question: ‘What is the current state of Curaçao’s electricity infrastructure?’

2.1 Introduction

Curaçao has an isolated electricity infrastructure that is not connected to the infrastructure of other countries. Therefore, only local electricity producers generate electricity, from both intermittent Renewable Energy Sources (RESs) and non-RESs. This isolated production makes it difficult for the local electricity supplier to ensure a secure power supply. The most common reasons for electricity shortages in Curaçao are: (1) technical failures; (2) unfavorable weather conditions for sustainable sources such as wind and solar energy; (3) an unexpected increase in power demand.

To provide insight into the current situation with Curaçao’s electricity infrastructure, we will describe the electricity infrastructure and its components in depth. The description is structured according to the structure also used by Glover and Sarma (2002), Kinney et al. (2005), Farhangi (2010), and Vittal (2010).

The remainder of this chapter is structured as follows:

- A short history of Curaçao’s electricity infrastructure (Section 2.2);
- A description of the Curaçao’s current electricity infrastructure (Section 2.3);
- An analysis of Curaçao’s electricity production (Section 2.4);
- Conclusions on Curaçao’s electricity infrastructure (Section 2.5).

2.2 A short history of Curaçao’s electricity infrastructure

In 1893, an American Consul named Leonard B. Smith was granted the right to produce and transport electricity in Curaçao. Smith built the first power plant at Plantersrust in Curaçao. Since its establishment in 1893, the electricity infrastructure has changed and grown considerably.

In 1897, the island of Curaçao was illuminated by electricity for the first time. Leonard B. Smith sold his right to produce and transport electricity in 1907 to Maduro & Sons, a local company in Curaçao. Twenty years later, Maduro & Sons sold the electricity company to a Dutch company, '*Nederlandsch-Indische Gas Maatschappij*' (NIGM). In 1950, this company changed its name to '*Overzeese Gas en Elektriciteit Maatschappij*' (OGEM). In 1977, the production, and distribution of gas and electricity were transferred from OGEM to the Island Territory. The Island Territory of Curaçao then split this company into two companies: '*Kompania di Awa i Elektrisidat*' (KAE) and '*Kompania di Distribushon di Elektrisidat i Awa*' (KODELA). The company KAE was in charge of the production of water and electricity, while KODELA was responsible for the distribution of electricity. In 1988, the part responsible for the production and distribution of water became a part of KODELA and, at the same time, the management of KAE and KODELA were merged to form a new entity, '*Integrated Utility Holding*' (IUH). In early 2001, IUH, KAE, and KODELA became Aquallectra Holding, Aquallectra Production, and Aquallectra Distribution respectively. In February 2001, a new company, '*Aquallectra Multi Utility*', became a subsidiary of IUH, and the management board of IUH became responsible for operating the companies (Aquallectra, 2015).

Currently, Aquallectra is the only company that distributes electricity and water in Curaçao. It is also the largest electricity and water producer in Curaçao. Since 2011, an independent regulatory agency, the '*Bureau Telecommunicatie, Post en Utiliteit*' (BTPU) regulates the tariffs and the energy policy. The main task of this agency is to monitor the following sectors: 1) the service providers and end users of telecommunication services and/or their products, 2) the postal sector, 3) the electricity sector, 4) the water distribution sector, and 5) the fuel sector (BT&P, 2015).

2.3 Curaçao's current electricity infrastructure

The main function of an electricity infrastructure is to transport electricity from power plants to customers. This infrastructure consists of electricity power plants, the transmission lines, and the distribution lines. The power plants generate the electricity, which the transmission lines transmit at high voltage to the substations where it is transformed to an intermediate voltage.

The distribution lines then distribute the electricity to several low-voltage transformers, where it is reduced to the voltage used by the connected end users.

2.3.1 The transmission and distribution of electricity in Curaçao

The transmission network, with 30 kV and 66 kV high-voltage lines, transports the electricity from the producers to the substations on the island. This transmission network is located underground. Since the 1990s, the voltage of the new transmission network has been set at 66 kV. The main reason for this increased voltage level is to reduce power losses. The 66 kV transmission network has two main power generating stations, located at the Isla refinery premises and at Dokweg, which are linked to each other through two 66 kV cables. The 30 kV transmission network consists of 14 substations, which are located at Juliana Plein, Nijlweg, Weis (two substations), Parera, Montagne, St. Barbara, Zegoe, Dokweg, Koningsplein, Parasasa, Mundu Nobo, Brievengat, and Tera Kòrá (see Figure 2.1). A 12 kV intermediate voltage distribution network distributes the electricity from the substations to various areas and to large customers. Further, a wind farm at Tera Kòrá is connected to the Tera Kòrá substation (30 kV), and a wind farm at Playa Kanoa is connected to the Brievengat substation (30 kV). Approximately 60% of the distribution network is underground.

The low-voltage network connects the distribution transformers with the end users. These transformers reduce the voltage from 12 kV to 127 V or to 220 V. This low-voltage network consists mainly of overhead lines. The typical amperage of the dwellings varies from 25A to 32A. Large customers, with a power capacity above 50 kVA have their own distribution transformers.

Figure 2.1: The transmission network on Curaçao (Aqualectra, 2018)

2.3.2 Electricity demand in Curaçao

Aqualectra, Curaçao's utility company, defines five main categories of electricity users: household, business, industry, hospitals, and public lighting ('Aqualectra', 2015). The largest categories in terms of electricity consumption in Curaçao are the household, industry, and business (including companies, government, and other type of organizations) sectors, which largely determine the load in Curaçao. Table 2.1 lists the electricity use per sector in 2017. The household sector is divided into post-paid and prepaid households. Prepaid indicates that the consumers purchase an 'electricity credit' in advance of service use, whereas post-paid consumers are billed at

the end of each month according to their electricity use. The industry sector consists of 'standard' industry, which produces goods and/or services for local use; the export industry, which produces goods and/or services for both export and local use; and the import industry, which imports goods and/or services for local use.

Table 2.1: Energy demand per sector in Curaçao (2017)

No	Sectors	Annual energy demand (MWh)
I a	Households Post-paid	210,330.90
I b	Households Prepaid	92,087.84
2	Business	154,793.63
3a	Standard industry	93,916.76
3b	Export industry	101,528.33
3c	Import industry	6,096.64
4	Hospitals	10,207.33
5	Public lighting	7
	<i>Total</i>	<i>676,272.19</i>

The electricity demand, as illustrated in Figure 2.2, is relatively constant throughout the day. During the working week, there are three peaks ('Policy Document Regulation Electricity Supply Curaçao 2011-2015', 2011).

Figure 2.2: Daily variation in electricity demand in Curaçao ('Policy Document Regulation Electricity Supply Curaçao 2011-2015', 2011)

The first electricity peak demand occurs in the morning at about 10.00, followed by the second electricity peak demand at approximately 15.00 in the afternoon, and a final electricity peak demand occurs at about 23.00. The first electricity peak demand is linked to many businesses commencing their operations, and the second electricity peak demand occurs at the hottest time of the day, when the air-conditioners in businesses and some homes are operating. The final electricity peak demand occurs when the air conditioners in homes are turned on. As illustrated in Figure 2.2, this third electricity peak demand is considerably lower than the other two peaks; which have almost the same magnitude of typically around 132 MW. Figure 2.2 also depicts the lower electricity demand at weekends. At the weekends, there is only the late evening peak demand when domestic users switch on their air conditioners. The lowest electricity demand is on Sundays between 07.00 and 10.00 because most businesses are closed on Sundays. Notwithstanding these demand fluctuations; the daily variations in electricity demand can fairly accurately be predicted by the utility company. Nevertheless, there are several electricity power outages and load shedding

occurrences in Curaçao. Temporary actions taken to reduce the electricity load of an area, when electricity demand is greater than electricity power supply, is known as load shedding. These electricity power outages and load shedding events frequently occur during particularly hot periods when customers intensify the use of air conditioners and increase the peak demand. Insufficient electricity power capacity is the main cause of these electricity power outages and load shedding.

This is frequently because electricity production from wind turbines is low because of lower wind speeds during hot periods.

Figure 2.3 illustrates the average monthly electricity demand in Curaçao ('Policy Document Regulation Electricity Supply Curaçao 2011-2015', 2011).

Figure 2.3: The average monthly electricity demand in Curaçao
(‘Policy Document Regulation Electricity Supply Curaçao 2011-2015’)

The electricity demand increases gradually from January until May, at which point the demand decreases steadily until July. From July, the demand increases again and reaches its maximum value at the beginning of October. After mid-October, the demand decreases once more. This decrease occurs because the temperature during the months of October to February is lower than in other months. In addition, more rain falls in these months than in the other months, and due to the ambient temperature in these months, which is lower than in the other months, the air conditioners are used less. Furthermore, in some dwellings, the temperature of the thermostat are set to a higher temperature during these periods. The growth in demand in July is the result of the holiday period.

2.4 Curaçao's electricity production

To meet the required demand, a diverse range of energy sources generate electricity in Curaçao. These sources include diesel generators, steam turbines, gas turbines, wind turbines, and photovoltaic (PV) systems. In this section, the energy sources of Aqualectra are first described, and then the total energy production system is presented.

2.4.1 Non-renewable sources

In total, the installed capacity of non-renewable sources is approximately 176.8 MW. Three diesel engine power plants, with capacities of 48.4 MW, 35.6 MW, and 38.8 MW are situated at Dokweg. The first plant went into operation in 1997, and was expanded in 2009 with two additional 5.3 MW units. This plant now consists of six units of 6.3 MW each and two units of 5.3 MW each. The second power plant with an output of 35.6 MW came online in January 2015. This power plant has four production units of 8.9 MW each. The newest, 38.8 MW, power plant, with four production units of 9.7 MW was inaugurated in April 2019.

Aqualectra also owns a diesel engine power plant, located at the refinery premises, with a capacity of 33.2 MW which became operational in 2008. This plant has four 8.3 MW production units.

A gas turbine with a capacity of 20.8 MW was installed at Mundu Nobo in 1979 and renovated in 2015. This turbine is only used when there is insufficient electricity from the other plants to supply all customers. It will soon be moved to the refinery premises.

In addition to the 176.8 MW installed capacity described above, the 'Curaçao Refinery Utilities' (CRU) in principle provides a minimum 45 MW from its over-production to Aqualectra. However, since the establishment of CRU in 2003, this amount of energy is frequently unavailable due to a range of technical problems that occur at this power plant. The steam turbines at CRU primarily produce electricity and steam for the refinery.

2.4.2 Renewable energy sources in Curaçao

This section describes the various renewable energy sources that generate electricity in Curaçao. To date, the total installed capacity from renewable sources is 60.5 MW. Given that the total installed capacity in Curaçao, which is the sum of all energy sources, is approximately 237.3 MW, about 26% of the installed capacity on the island is provided by RESs.

Electricity production by wind turbines

In 1985 Kodela (nowadays part of Aqualectra) installed, as an experiment, its first wind turbine with 24 meter long blades at San Pedro in Curaçao. This wind turbine, which was connected to the substation at Tera Kòrá, had a capacity that could supply energy to 200-300 households. Since this first trial, the application of wind energy has considerably increased in the last few decades. In July 1993, the first commercial wind farm in the Caribbean was installed at Tera Kòrá in Curaçao. This wind farm, which was owned by Aqualectra, had 12 wind turbines of 250 kW each with a total installed capacity of 3 MW. This wind farm performed above all expectations ('Nucapital', 2015). After this success, the company Nucapital installed another wind farm in Curaçao. This was located at Playa Kanoa and consisted of 18 500 kW wind turbines, with a total installed capacity of 9 MW. Both wind farms are situated on the windward coast of Curaçao. Later, Nucapital purchased the wind farm at Tera Kòrá. In July 2012, the updated and renovated wind farms at Tera Kòrá (TKO 1) and Playa Kanoa (PLK) were

commissioned. Each wind farm then consisted of five Vestas 3.0 MW wind turbines, with a combined installed wind capacity of 30 MW. In 2017, the Tera Kòrá wind farm was expanded to include an additional five Vestas 3.3 MW wind turbines (TKO 2). This resulted in a total installed wind capacity in Curaçao of 46.5 MW. As such, wind energy accounts for approximately 20% of Curaçao's total installed electricity power and produces about 234 GWh (see also Table 2.2) per year, which is approximately 31% of the total electricity production ('Nucapital Curaçao bv', 2017).

Table 2.2: Electricity production of wind farms at Playa Kanoa, Tera Kòrá I and Tera Kòrá 2 (Aqualectra, 2019)

2018	kWh PLK	kWh TKO I	kWh TKO 2
Jan	6,258,200	5,541,200	9,628,400
Feb	5,507,000	5,715,600	8,352,000
Mar	5,498,600	5,786,400	8,646,000
Apr	5,762,900	5,478,000	8,563,200
May	7,699,500	7,690,000	1,1374,400
Jun	6,368,000	6,519,600	9,595,600
Jul	5,610,500	5,786,400	9,380,400
Aug	6,086,100	6,478,800	9,987,600
Sep	3,875,200	4,390,400	7,108,000
Oct	2,767,700	2,862,800	5,129,200
Nov	2,823,400	3,838,800	6,132,400
Dec	5,886,600	6,041,600	9,590,400
<i>Total per windfarm</i>	<i>64,143,700</i>	<i>66,129,600</i>	<i>103,487,600</i>
<i>Total wind</i>	<i>233,760,900 kWh</i>		

Table 2.2 shows a high fluctuation in wind electricity production during the year. This fluctuation is primarily caused by wind speed variations and the need for servicing and maintenance of the wind turbines. Wind-based electricity production during October and November is relatively low due to lower wind speeds and the fact that servicing and maintenance is scheduled in these months with weak wind speeds. In contrast, peak wind electricity production occurs in the months of January, May, June, July, August, and December. The main challenge for the utility company is to balance the variations in the wind electricity production when the wind speed fluctuates. This requires backup power equivalent to the total power capacity of the wind farm. Nowadays, highly reliable forecasts of wind speed and direction can be provided. This helps the utility companies to minimize the risk and uncertainty of wind power integration. With this, the backup can be scheduled more accurately, which can provide substantial cost savings. In Curaçao, and in many other SIDS, the backup power for renewable energy is still provided by fossil fuels. This type of backup has a negative impact on the environment. Nowadays, there are several energy storage technologies, such as batteries, flywheels, and thermal energy storage that can be used to compensate for short electricity fluctuations. Chapter 5 will elaborate on some of these energy storage technologies.

Apart from the wind farms at Playa Kanoa and Tera Kòrá, there are also a few small wind turbines installed within the electricity infrastructure. The total power generated from these small wind turbines is negligible compared to the bigger wind farms at Playa Kanoa and Tera Kòrá. Small wind turbines have some disadvantages, the most important being (Boyle, 2009):

1. not all locations are suitable for the production of wind energy;
2. many times, surrounding buildings, trees, and other obstacles will affect the electricity production to such an extent that it is not viable;
3. due to the local climate condition in Curaçao, these wind turbines are affected by corrosion, and this can result in a short lifespan; and
4. wind turbines contribute to noise and visual pollution.

Appendix I gives an overview of the production of three small wind turbines installed in Curaçao.

Electricity production by Photovoltaic (PV) power systems

The conversion of the energy carried by optical electromagnetic radiation into electrical energy is a physical phenomenon known as the photovoltaic (PV) effect. Solar cells are the most common device used to effect this conversion. In 1839, the PV effect was observed for the first time by the French Physicist Becquerel. In 1954, Chapi, Fuller, and Pearson presented the first reasonably efficient silicon solar cells and, since then, similar devices have been used around the world. PV cells convert the energy of solar light directly into Direct Current (DC) electricity (Reinders, Verlinden, van Sark, & Freundlich, 2017).

In general, PV systems consist of the PV modules plus the balance of system (BOS) components. The BOS components include the support structures for mounting the modules, the cables, the junction boxes, the transformers, and an inverter which is necessary in grid-connected PV systems. The inverter transforms the DC from the PV module into alternating current (AC) (Jungbluth, Tuchschnid, & de Wild-Scholten, 2008; Liu, Kent Hoekman, Robbins, & Ross, 2015; Sumper, Robledo-García, Villafáfila-Robles, Bergas-Jané, & Andrés-Peiró, 2011). Generally, the electrical equipment in buildings in Curaçao requires an AC supply. The basic configuration of PV systems are the same for all sectors, but they can vary greatly in size from small PV systems for households to large PV systems for the commercial and industrial sectors.

Before 2010, it was impossible to connect any renewable energy source apart from wind turbines to the electricity infrastructure of Curaçao. After October 10, 2010, when Curaçao became an autonomous country, the existing energy legislation and energy policy was renewed. In late 2011, it became possible to also connect other types of renewable energy sources, such as Photovoltaic (PV) power systems, to the electricity infrastructure. PV power systems were installed in the household sector, at schools, and in large and small businesses. The conditions were favorable and, if properly installed, the average payback period for PV systems was between two and a half and three years. As a consequence, within approximately three years, the installed PV power systems increased dramatically from 0 kW to more than 12 MW. This success was in part due to end-users receiving the same

rate (approximately 0.41 USD per kWh) as they paid for electricity delivered for any unused surplus electricity that was being uploaded to the grid. End-users also did not have to pay any additional fixed monthly fee for having installed panels.

With many households and companies installing solar panels, the sales and consequently the revenues of Aquallectra started to drop. After an analysis of the situation, the regulatory agency BTPU introduced a much lower feed-in tariff in 2011 of 0.18 USD per kWh and also a standby / back up component charge of 9.00 USD per kWp installed for households and 18.00 USD per kWp for businesses. The level of the feed-in tariff and the fixed monthly fee are evaluated each year in line with the tariff guidelines for small-scale sustainable electricity provision (2011). Based on the tariff guidelines, the government has regularly adapted the feed-in tariffs and the fixed monthly fee. The fixed monthly fee that BTPU retains is determined according to international trends and based on payback periods of 7-10 years for installed PV systems. The feed-in tariff is adjusted in line with changes in fuel price ('Adaptation tariffs renewable electricity generation', 2018).

It is important to note that if the tariffs are not set correctly then this could adversely affect the utility company, the customers with solar panels as well as the customers without solar panels. For instance, if the feed-in tariff is too high and/or the fixed monthly fee too low, the utility company will incur losses or the customers without solar panels will have to pay more. Conversely, if the feed-in tariff is set too low and/or the fixed monthly fee too high, this will discourage investment in PV systems because the resulting payback period may be considered as too long. Generally speaking, feed-in tariffs are used as policy instruments to encourage investments in renewable energy systems. This tariff can be generous in the short term to promote investments in renewable energy systems. However, after a promotional period, feed-in tariffs are often reduced to a realistic level that does not adversely affect either the customers or the utility company.

Table 2.3 summarizes the rates per category before and after the adjustments (BTP, 2018).

Table 2.3: Photovoltaic power system fees

Sector						
	Residential	Commercial	Industry standard	Industry export	Industry import	Hospital
Period	Feed-in tariff [USD]					
Before 2015	*Balanced	0.234	0.234	0.234	0.234	0.234
Jan - Dec 2015	0.180	0.180	0.180	0.180	0.180	0.180
Since Jan 2016	0.136	0.136	0.136	0.136	0.136	0.136
	Fixed monthly fee [USD/kW]					
Jan 2015 - Dec 2017	9	18	18	9	18	9
Since Jan 2018	4.5	9	9	4.5	9	4.5

*Balancing: household sector feed-in tariff same as the electricity rates in this sector.

In total, there are approximately 760 PV systems installed in Curaçao (Aqualectra, 2017). To provide some insight into how solar panels perform in Curaçao, Table 2.4 provides an overview of the production of four different PV systems in Curaçao (Eco-energy, 2015). Table 2.4 shows that the fluctuation in PV electricity production during the course of a year is quite small. However, during an individual day, variation in irradiance, as a consequence of change in cloud cover, can induce rapid variations in PV electricity production. Predicting the variation in irradiance is difficult and so the utility companies must ensure there is always backup available to balance out fluctuations in PV electricity production when the irradiance changes. Further, Table 2.4 shows that the PV electricity production is less in the months of November and December. Given that November is also a rather unproductive month for the wind turbines makes it even more difficult for the utility company to guarantee constant power quality and reliability, especially, if one or more of their fossil fuel generators are not in service in this period. However, storage technologies, such as batteries, may be able to more effectively compensate for short-term electricity fluctuations than fossil fuel sources.

Table 2.4: Electricity production from four photovoltaic systems
(Eco-energy, 2015)

Month	PV system 1: 5.5 kWp	PV system 2: 5.94 kWp	PV system 3: 15.4 kWp	PV system 4: 6.72 kWp
	Production [kWh]			
January	756	541	1333	821
February	752	595	1317	805
March	866	795	1526	983
April	826	835	1368	943
May	780	871	1351	981
June	747	867	1275	961
July	794	917	1358	1000
August	875	900	1455	1029
September	755	718	1338	913
October	786	610	1329	858
November	695	489	1208	761
December	699	441	1237	771
Average	778	715	1341	902

As can be seen in Table 2.4, some PV systems perform better than the others. This is because PV electricity production depends on various factors including irradiance, panel efficiency, shading, orientation of the panels, angle of inclination of the panels, temperature of the panels, power loss due to soiling of the panels, and power loss in the cables and BOS components (Dunlop, 2010).

2.4.3 Total electricity generation by non-RESs and RESs

The previous two subsections illustrate how the role of sustainable energy sources has considerably increased in Curaçao in the past few years. Table 2.5 gives an overview of the total electricity power and electricity production in Curaçao in 2019, for RESs as well as non-RESs.

Table 2.5: Total electricity power and electricity production in Curaçao

No	Energy sources	Installed Power [MW]	Production [GWh/year]
1	Gas turbine	20.8	n/a
2	Dokweg I	48.4	n/a
3	Dokweg 2A	35.6	n/a
4	Dokweg 2B	38.8	n/a
5	NDPP	33.2	n/a
Total non-RESs		176.8	446
5	Solar	14	19
6	Wind turbines PLC	15	65
7	Wind turbines TCO	31.5	146
<i>Total wind energy</i>		46.5	211
Total RESs		60.5	230
Total (all sources)		237.3	676

The total installed power capacity (237.3 MW) is considerably higher than the electricity peak demand (130 MW). However, if one or more of the fossil-fuel sources are not in service (defect and/or maintenance), and there is little or no wind and sun, the installed power capacity is not sufficient to meet the electricity demand.

Currently, renewable energy (solar and wind energy) accounts for about 26% of Curaçao's total installed electricity power capacity and produces roughly 230 GWh/year, which is approximately 34% of the total electricity production. The share of electricity production from intermittent RESs is relatively high in Curaçao when compared with other countries. Table 2.6 includes an overview of the countries with a share of electricity production from intermittent RESs higher than 20% in 2017. Curaçao ranks no 2 on this list behind Denmark.

Table 2.6: Countries with a share of electricity production from intermittent RESs higher than 20% ('Renewables 2018', 2018)

No	Countries	Share of electricity production from RESs
1	Denmark	53%
2	Curaçao	34%
3	Uruguay	28%
4	Germany	26%
5	Ireland	25%
6	Portugal	23%
7	Spain	21%

Denmark has by far the highest share of electricity production from RESs. The transmission system in Denmark consists of two separate transmission networks covering the western and eastern parts of the country. A very relevant feature here is that the Danish transmission networks are interconnected with the transmission infrastructures of Germany, Norway and Sweden (Sorknaes, Maeng, Weis, and Anderson, 2013). Such cross-border interconnected networks improve the security of the electricity production and enable greater penetration of intermittent RESs. That is, cross-border interconnections make it easier to manage intermittent renewable-energy sources.

Aqualectra aims to further increase the share of electricity production from intermittent RESs to 45% (see Chapter 5). Furthermore, and as stated in Chapter I, the goal of this study is to develop a roadmap towards a fully renewable energy system for Curaçao.

2.5 Concluding remarks on Curaçao's electricity infrastructure

This chapter has provided an overview of the current state of Curaçao's electricity infrastructure and the power plants in Curaçao. As in all countries, the demand for electricity is not constant and constantly varies throughout the day depending on the activities of the users. As this chapter

demonstrated, Curaçao already has a relatively high proportion of its electricity produced from intermittent RESs.

In designing a fully renewable energy production system for Curaçao, the following three design constraints will need to be considered:

- The electricity production from wind turbines in Curaçao fluctuates significantly during the year. These fluctuations are caused by the variable wind speed, and by the required downtime for service and maintenance of the wind turbines.
- Variation in irradiance due to changes in the cloud cover results in rapid changes in PV electricity production throughout the day.
- Energy storage will need to be utilized to compensate for these short-term electricity fluctuations.

CHAPTER 3

Examining energy use and energy behavior in Curaçao

In this chapter, the second research question will be answered: “What is the status of energy use and energy behavior in the household, commercial, and industrial sectors in Curaçao?”. In order to answer this question, in addition to a study of relevant literature, documents, and reports, four surveys were conducted in the household, office buildings, hotel, and supermarket sectors respectively. Although several studies have been conducted elsewhere on energy use and behavior, no literature is available on detailed energy use and energy behavior specifically related to Curaçao. In response, this study provides insights into the energy use and behavior of residents, the commercial sector, and the industrial sector of Curaçao.

The outline of this chapter is as follows.

Section 3.1 provides an introduction on international developments in energy use. Section 3.2 elaborates on the characteristics that influence energy use of households and then Section 3.3 provides characteristics of households in Curaçao (family size and income levels). Section 3.4. provides the details of a survey that was conducted among 384 households in Curaçao to investigate their energy use and to discover relevant factors that influence household energy behavior. Section 3.5. presents the results of the conducted survey, followed by an in-depth analysis.

Besides the energy use by households, the energy use in office buildings, hotels and supermarkets was also examined. Section 3.6 describes and analyses the results of a survey conducted on energy use covering 333 office buildings in Curaçao, Section 3.7 describes the energy use in hotels in Curaçao and, in Section 3.8, the energy use of nine of the larger supermarkets are presented and discussed. The chapter ends with conclusions on energy use and energy behavior in Curaçao in Section 3.9.

3.1 Introduction to international developments in energy use

The world's energy use is expected to increase by 48% between 2012 and 2040, or by approximately 1.4% per year ('*International Energy Outlook 2016*', 2016). Most of this growth will come from non-OECD (Organisation for Economic Co-operation and Development) countries, including many countries where demand is driven by strong economic development. In 2040, the energy use in the industrial sector will account for approximately 53% of the total energy demand, followed by the transportation sector with approximately 26%, and the building sector (household and commercial) with roughly 21% of the total energy demand. As such, the industrial sector will remain the largest energy-consuming sector. Nevertheless, the energy share of the industrial sector is expected to decrease by approximately 1% per year in the period 2012 to 2040. This is because the use of energy-intensive manufacturing processes will decrease, especially in non-OECD countries. The energy shares of the transportation sector and the building sector are expected to increase by about 1% per year. In non-OECD nations, energy use in the building sector will increase due to rapid economic growth and increasing standards of living. In the OECD nations, the energy use in the building sector is expected to increase slowly due to a rather slow growth in population and GDP, as well the increasing use of energy-efficient appliances and energy-efficient building improvements. Economic growth will also influence energy use in the transport sector. Almost all energy growth in the transport sector is expected to occur in developing countries. The growth in living standards in these countries, as a consequence of economic growth, will lead to more personal travel and freight transport. Energy use in the transport sector in the OECD nations will grow only slowly, due to the slow economic and population growth and vehicle energy-efficiency improvements ('*International Energy Outlook 2016*', 2016).

3.2 Factors that influence household energy use

To date, several studies have demonstrated that there are various factors that influence domestic energy use. Many governments have attempted to make household buildings more energy-efficient by introducing policies and regulations to reduce energy use in these buildings. It should be noted that

notwithstanding all these actions, the energy saving results are lower than expected (Guerra Santin, Itard, & Visscher, 2009). Simply implementing various energy-efficiency measures is not enough – for these to work it is essential to understand building characteristics, and the energy use and energy behavior of their occupants.

The International Energy Agency (IEA) (2016) indicated that income levels, energy prices, location, building and household characteristics, weather, efficiency and type of equipment, energy access, availability of energy sources, energy-related policies, energy behavior, education level, energy awareness, region, and country are the main factors that affect domestic energy use.

Energy price is a factor that is considered in many studies. A progressive electricity tariff system, which involves a higher kWh price for increased electricity use, or high electricity tariffs in general can influence energy use. High prices encourage consumers to purchase energy-efficient appliances as well as to think more about domestic energy use (Banfi, Farsi, Filippini, & Jakob, 2008; De Martino Jannuzzi & Schipper, 1991; May & Brennan, 2006). More recently, the World Energy Council (WEC, 2012) emphasized in its annual report that a high energy price contributes strongly to improved energy efficiency.

Environmental awareness is often used as a factor to stimulate energy efficiency in the household sector (Aldossary, Rezgui, & Kwan, 2015; Ek & Söderholm Patrik, 2010). However, conclusions about the effects of environmental awareness are mixed. Wang, Zhang, Yin, and Zhang (2011) and Hori, Kondo, Nogata, and Ben (2013) indicated that environmental knowledge and environmental awareness do not influence energy use. Rather, domestic energy use is largely determined by two factors, namely the occupant's energy behavior and technological aspects (Carlsson-Kanyama, Lindén, & Eriksson, 2005; Hori et al., 2013; Ouyang & Hokao, 2009). Globally, the focus tends to be more on the technological aspects than on user behavior despite consumers' energy behavior being as important as the technological aspects, such as the use of energy-efficient appliances (Ouyang & Hokao, 2009). In part this is because the use of energy-efficient appliances depends strongly on the energy behavior of the

consumer. Another influencing factor is what is labeled the rebound effect, in which an energy-efficient appliance is used for a longer period than the previous less-efficient one because this appliance costs less to run (Abrahamse, 2007).

Van Raaij and Verhallen (1983) classified energy-related behaviors as follows:

1. purchase-related behavior — this refers to behavior when purchasing domestic appliances and considering the energy use of the appliances. For example, energy-efficient appliances are generally more expensive at the point of sale but less expensive in use. Nevertheless, the price of appliances is often the determining factor;
2. maintenance-related behavior — this type of behavior has to do with the maintenance of domestic appliances, small repairs, and home improvements, such as installing improved insulation; and
3. use-related behavior — this refers to the everyday, energy-conscious use of appliances, for example setting thermostats, switching off appliances when they are not needed, and closing curtains.

To summarize, energy use in the household sector depends on various factors. The main factors are the occupants' behavior and level of income, and technological aspects. The purchase of energy-efficient appliances, home improvements, and energy-conscious use of appliances are all strongly dependent on energy behavior as well as on the income level of the occupants. Furthermore, policies, regulations, and energy prices can influence the energy behavior of occupants. It is important to note that, in various countries, energy savings in the household sector have been lower than were expected, notwithstanding several energy saving actions having been taken (Guerra Santin, Itard, & Visscher, 2009).

3.3 Household characteristics in Curaçao

Curaçao has over 150,000 inhabitants, and about 65,225 dwellings (CBS, 2011). The number of occupied dwellings is 54,936, with the remaining 10,289 being either unoccupied or temporary dwellings. The bureau of statistics in Curaçao classifies approximately 15.8% of the dwellings on the island as unoccupied. It also divides the unoccupied dwellings into six

categories: (1) new built dwellings, which have not yet been inhabited (approximately 9.6% of the total of unoccupied dwellings); (2) holiday rentals, which are used by Curaçao inhabitants as well as tourists (16.4%); (3) dwellings under construction (17.7%); (4) dwellings inhabited by people who are temporarily staying on the island (5.5%); (5) currently unoccupied dwellings that have been inhabited in the past (48.7%); and (6) unclassified (2.2%).

Table 3.1 illustrates household sizes against household income. CBS classifies household income in Curaçao into three categories: a minimum income category, the middle-income category, and the maximum income category. The minimum income category covers households with a monthly average income of less than USD 1,125. A monthly average household income between USD 1,125 and USD 2,808 is placed in the middle-income category. Finally, a monthly average gross household income that exceeds USD 2,808 falls into the maximum income category.

It can be seen that two people constitute the most common household size in Curaçao. Such households account for approximately 37.8% of all households in the low-income category, 28.9% of the middle-income category, and 25% of the high-income households. The average household size in Curaçao is about 2.7 people. These household sizes are not dissimilar to those seen in Europe. According to Dennehy and Howley (2013), the average household size in 2011 was 2.0 in Denmark and Germany. In the UK, the average size was 2.3, while in the EU as a whole, it was 2.4.

Table 3.1: The household size, number of persons (p) per household versus income categories

Household size	1p	2p	3p	4p	5p	6p	>6p	Total
Low income [%] < \$1,125	25.9	37.8	16.8	10.3	4.9	2.9	1.6	100
Middle income [%] \$ 1,125 - \$ 2,808	14.1	28.9	23	23.0	7.4	3	0.7	100
High income [%] > \$ 2,808	12.5	25	18.8	25.0	9.4	7.8	1.6	100
All households [%]	20	33	19	17	7	4	1	100

3.4 Household energy use survey in Curaçao: Research approach

As was discussed in Section 3.2, the implementation of various energy efficiency measures in the household sector in several countries has led to lower than expected energy savings. It is therefore seen as essential to understand the household characteristics, energy use, and energy behavior of occupants. A literature study and a survey covering 384 households in Curaçao were conducted to identify household energy use; the factors affecting energy behavior; and the relationships between energy use, energy behavior, and household income.

Households were randomly selected to participate in this survey. To ensure a maximum margin of error of 5% with a confidence interval of 95%, a minimum number of 382 households was required. In total, 857 of the 65,225 households were approached to participate in the survey and 384 households joined this survey.

A questionnaire consisting of 12 open-ended questions was designed for this survey (see Appendix 2), which was carried out by telephone over a period of four months. The calls were made during daytime and evening hours by students from the Faculty of Engineering of the University of Curaçao (UoC). The students were provided with the necessary instructions to conduct the interviews by myself as their supervisor. Progress was monitored on a regularly basis.

The procedure of the telephone survey that was used was as follows:

1. the interviewer introduces himself/herself;
2. the interviewer gives a short and clear description of the survey;
3. the interviewer explains the procedure of the survey;
4. the interviewer provides the estimated time needed to complete the survey;
5. the interviewer asks the respondent to join the survey; and
6. after having completed the survey, the interviewer extends gratitude to the respondents.

A telephone survey has advantages, but also disadvantages. The main advantages of a telephone survey were the associated good accessibility, given that most households in Curaçao have fixed-line telephones, and that it is an easy and quick process. The main disadvantages of this method are that the interviewer cannot see the body language of the respondents, the questions must not be too complex, and the respondents will be less motivated to join the survey if the time that they were approached was inconvenient. Indeed, in the conducted survey, the interviewers had to call some respondents back because the time of the initial call was inappropriate for the respondents. The collected data from each dwelling and household were then processed. Following this, the electricity use of the appliances claimed was estimated by multiplying the number of appliances by the average electricity use that the local utility company, Aqualectra, provided.

3.5 Household energy use survey in Curaçao: Results and analysis

This section presents the results and analysis of a survey that was conducted in the household sector of Curaçao.

This section consists of four subsections:

- Subsection 3.5.1. provides an overview of the number of dwellings per household size and also the number of dwellings per income category;
- Subsection 3.5.2. provides details about the motives that occupants have to save energy and the energy saving methods that they apply;

- Subsection 3.5.3. provides details about the energy use per type of appliance that is used, divided by income category; and
- Subsection 3.5.4. considers the three most energy-consuming appliances used in Curaçao and concludes that these appliances have large, yet to be applied, energy saving potentials.

3.5.1 Number of dwellings per household size and per income category in Curaçao energy survey

In total, 857 households were approached to participate in the survey, of which 384 (44.8%) agreed to join. Table 3.2 provides an overview of the household sizes in terms of the number of persons (p) living together in each house.

Table 3.2: The household sizes (n=384)

Household sizes	1p	2p	3p	4p	5p	6p	> 6p	Total
Number of households	75	125	74	66	25	14	5	384

Table 3.3 presents an overview and frequencies of the income categories obtained from CBS ('CBS', 2011) and the survey.

Table 3.3: The frequencies of income categories

Income categories	No of households & Frequency (%)	
	Census 2011	Survey
Low income < \$ 1,125	16495 (30%)	185 (48%)
Middle income \$ 1,125 - \$ 2,808	17707 (32%)	134 (35%)
High income > \$ 2,808	18251 (33%)	65 (17%)
Unknown	2483 (5%)	0 (0%)

Nearly half of the households in the Curaçao energy survey have a low income, while 35% (134) have a middle-level income, and 17% (65) of the households have a high income (Table 3.3).

3.5.2 Household sector energy behavior in Curaçao

This subsection gives the results of the survey regarding energy behavior in the household sector in Curaçao.

With regard to the question “Do you take actions to save energy”, 373 of the participants responded that they did take actions to save energy, while 11 of the respondents answered that they did not. The respondents were also asked for the reasons why they tried to save energy. The results revealed that financial issues were the main reason for energy saving, followed by environmental issues (Table 3.4). The percentage of households that save energy for environmental reasons is higher in the higher income households and the percentage that save for financial reasons is lower in these households. These results are in line with a study conducted by Owen and Videras (2006) that showed that citizens in the low-income category are less willing to save energy for environmental reasons.

Table 3.4: Motives to save energy according to income categories

Motives	Low income < \$ 1,125	Middle income \$ 1,125 - \$ 2,808	High income > \$ 2,808	Total
Financial	153 (83%)	96 (71%)	39 (61%)	288 (75%)
Environment and financial	3 (1.6%)	7 (5%)	1 (2%)	11 (2.9%)
Environment	24 (12.9%)	27 (20%)	22 (34%)	73 (19%)
Other reasons	1 (0.5%)	0 (0%)	0 (0%)	1 (0.2%)
No motives (do not take action)	4 (2%)	5 (4%)	2 (3%)	11 (2.8%)
<i>Total</i>	<i>185 (100%)</i>	<i>135 (100%)</i>	<i>64 (100%)</i>	<i>384 (100%)</i>

Table 3.5 summarizes the energy-saving methods reported during the telephone survey and the number of times they were applied in the households by income category. The number of households per income category is given in Table 3.3.

When asked whether they took actions to save energy, over 96% of the respondents in the three income categories responded that they did. The respondents were also asked how they saved energy. Hori et al. (2013) noted that the first step that citizens take in moving towards more energy-saving behavior is switching off lights. As can be seen in Table 3.5, the results of this survey are consistent with Hori et al. (2013). The switching off of lights and appliances was the most common action in the Curaçao survey, and for all the income categories. Although most of the respondents stated that they took action to save energy, the results of the survey indicate that they applied only the basic methods of energy saving.

Table 3.5: Number of times energy savings methods were applied

No	Savings methods	Low Income (n=185)	Middle income (n=134)	High income (n=65)	Total (n=384)
1	Energy saving air conditioner (AC) and less lighting	4	3	0	7
2	Energy star appliances	1	1	1	3
3	Energy saving AC and lights	3	3	3	9
4	Daylight and energy saving lights	2	4	2	8
5	Energy saving lamps	18	23	20	61
6	LED lamps	0	0	1	1
7	Use less lights	47	27	6	80
8	In general, use less electricity	30	10	6	46
9	Turning off lights and appliances when they are not used	54	42	14	110
10	Turn off indoor and outdoor lights before going to sleep	5	3	0	8
11	Turn off lights and appliances, when they are not used/installed motion detector	1	1	0	2
12	Use less AC and less lights	12	10	7	29
13	Use less AC	2	5	1	8

The survey results showed a positive correlation between household income and the application of energy-efficient appliances. High-income citizens can more easily purchase energy-efficient products than low-income citizens, whereas low-income citizens took more action in the sense of switching off appliances and lights when not in use. The results of the survey are also consistent with the results of Yue, Long, & Chen (2013). According to Dennehy and Howley (2013), households with higher incomes often reside

in newer and larger households and have both more appliances and more energy-efficient features. When household incomes are low, the citizens are less likely to purchase energy-efficient appliances; however, they take other actions to save energy. The respondents in this survey did not seem aware of all the available energy-efficiency options such as intelligent power bars, inverter appliances, time switches, motion sensors, and insulation. They consequently used only basic methods to save energy. The survey indicates that energy-saving air conditioners and lamps are the most frequently used energy-efficient appliances in the dwellings.

Many studies have indicated that awareness is one of the factors that influences energy saving. For instance, Hori et al. (2013) suggest that there is a positive relationship between awareness and energy saving. In our survey, we asked the respondents whether energy saving should be promoted in Curaçao and why. About 90% of the respondents from both the low-income and the middle-income categories responded yes, while approximately 80% of the respondents in the high-income category agreed. Most of them cited the following reason: that they need more information about energy saving.

3.5.3 Electricity consumption by type of appliance and income level by households in Curaçao

Table 3.6 lists the types and the number of appliances in households by income category in Curaçao obtained from the survey and the total energy use of these appliances per year. The average electricity use of the appliances was obtained from various sellers and the electricity company of Curaçao. It is important to note that one household can have more than one appliance of the same type. Furthermore, the number of households per income category is given in Table 3.3.

Table 3.6: The number of appliances and the total energy use of these appliances per year

Appliances	Low-Income (n=185)	Middle-Income (n=134)	High-income (n=65)	Total (n=384)	Energy use [kWh/year]
TV	185	134	64	383	114,976
Cable	97	120	61	278	41,366
DVD	82	104	59	245	235
Internet/ADSL	69	108	56	233	5,117
Computer	83	113	59	255	146,880
Refrigerator	183	135	64	382	543,005
Washing machine	167	131	61	359	131,021
Freezer	49	44	13	106	141,446
Radio	159	122	57	338	6,084
Microwave	62	89	44	195	19,188
Fan	113	133	43	289	58,262
Air-conditioner	75	103	57	235	558,444
Indoor lighting	1266	1358	957	3581	521,745
Outdoor lighting	618	695	490	1803	164,434
<i>Total energy use by appliances in households in Curaçao</i>					2,452,203

3.5.4 The three most energy-consuming appliances in the households in Curaçao

Figure 3.1 graphically presents the relationship between the electricity consumed by household appliances and household income categories. The largest electricity end-use in the low-income category is indoor lighting (25.1%), followed by air conditioners (18.2%), and refrigerators (18.1%). In the middle-income category, the largest cause of electricity consumption is air conditioning (26.3%), followed by indoor lighting (19.8%) and refrigerators (17.5%). The largest source of electricity consumption in the high-income category is air conditioning (27.5%), followed by indoor lighting (22.7%) and refrigerators (15.7%).

Figure 3.1: Household electricity end use among households in Curaçao

Comparing CBS data and Survey results

The differences between the survey results on appliance penetration rates in the household sector and the results of the 2011 census are relatively small. As would be expected, penetrations rates in our survey showed a slight increase on the earlier census. An appliance's penetration rate is the percentage of dwellings having the said appliance.

The appliance's percentage rate is calculated as follows:

$$\text{Appliance's penetration rate} = \frac{\text{number of appliances}}{\text{Total number of dwellings}} * 100\% \quad \text{Equation 3-1}$$

Table 3.7 provides an overview of the domestic appliance penetration rates.

Table 3.7: Appliance's penetration in the household sector

Appliances	Survey results [%]	Census 2011 [%]
Air conditioner	61.2	54.2
Computer	66.4	62.8
Fixed Internet	60.7	53.2
Freezer	27.6	24.8
Refrigerator	99.5	97.5
Television	99.7	92.9
TV decoder	72.4	67.9
Washing machine	93.5	91.3

The energy savings potential and energy saving opportunities in Curaçao will be further discussed in detail in Chapter 4.

3.6 Energy use in office buildings in Curaçao

Since no data were available regarding energy use in the commercial sector in Curaçao, a survey was conducted to collect this information. This survey was helpful in developing insights into the ways in which the commercial sector in Curaçao use energy, to find out details about their energy behavior, and to investigate the potential relationship between energy use and business size. This section presents the results of the study conducted on the energy use in office buildings in Curaçao. This section consists of two subsections:

- Subsection 3.6.1 explains the research steps that were taken to conduct the survey on energy use in office buildings in Curaçao;
- Subsection 3.6.2 provides the results and analysis of the survey about energy use in office buildings in Curaçao.

3.6.1 A survey about energy use in office buildings in Curaçao: Research approach

A survey was conducted to identify businesses' energy use, their energy behavior, and the relationship between energy use and business size. The office buildings to potentially participate in the survey were randomly selected from the yellow pages of Curaçao's telephone book. To ensure a margin of error of no more than 5% with a confidence interval of 95%, the sample needed to include at least 333 office buildings. In total, 1072 of the 2512 identified office buildings were approached to participate in the survey and 333 office buildings agreed to join this survey. A questionnaire consisting of 11 open-ended questions was designed for this survey (see Appendix 3). The survey was conducted by telephone interviews over a period of four months.

To gather information about the size of the office buildings, the first question addressed the number of employees in the respective business. Furthermore, to understand the energy use in the commercial sector in Curaçao, several questions related to the number, wattage, and type of appliances used. The results of the survey and detailed information about the size of the businesses, the appliances that are used in these office buildings, and the energy saving awareness provided answers to our fundamental questions related to energy use and energy behavior in the commercial sector in Curaçao.

The procedure for the telephone interviews in this survey was the same as that for collecting data about energy use by households in Curaçao (see Section 3.3). After explaining the procedure of the survey, the interviewer asked to speak to the person who would best be able to answer the survey's questions. In some cases, the interviewer agreed to send the questions by mail to the respondents. This was not the case in the domestic survey. Furthermore, the interviewers had to call some respondents back several

times because the time when they called was inappropriate for the respondents.

Finally, the data collected from all the office buildings were processed. Following this, the energy used by the appliances was estimated by multiplying the appliances' average wattages by the number of hours they are in use.

3.6.2 A survey about energy use in office buildings in Curaçao: Results and analysis

This subsection presents the results of the survey that was conducted in the business sector in Curaçao. This subsection consists of three sub-subsections: first, information is provided about business characteristics such as business scale, revenues and number of employees, and the type and number of appliances that are used and their respective energy use. This sub-subsection is followed by a sub-subsection about the energy use per appliance. In the last sub-subsection, energy awareness in the commercial sector is discussed.

Business characteristics

Curaçao has about 2,512 businesses, and CBS divides them into four categories (Martha, 2011). The categorization by CBS is as follows:

1. The micro-business group:
Micro-businesses employ fewer than 5 people and have revenues below 280,000 USD per year.
2. The small business group:
Small businesses employ 5-10 people and have revenues of about 280,000 USD per year.
3. The middle business group:
Middle businesses employ 10-50 people and have revenues between 280,000 USD and 2.8 million USD.
4. The large business group:
Large businesses employ more than 50 people and have revenues of 2.8 million USD or more.

In total, 333 out of the 1072 (31%) office buildings approached agreed to participate in the survey. Table 3.8 lists the number of participants that participated in this survey by business size.

Table 3.8: Number of participants by business' categories

Categories	Revenues and number of employees	Number of participants
Micro- businesses	< 280,000 USD and < 5 employees	100 (30%)
Small businesses	About 280,000 USD and 5 – 10 employees	83 (25%)
Middle businesses	280.000 USD – 2.8 mln USD and 10 – 50 employees	117 (35%)
Large businesses	> 2.8 mln USD and > 50 employees	33 (10%)
<i>Total</i>		333 (100%)

Table 3.9 provides an overview of the number and types of the main appliances in the offices for each business category.

Table 3.9: An overview of the number and types of the appliances

Appliances	Micro Number of Appliances n=100(Avg)	Small Number of Appliances n=83(Avg)	Middle Number of Appliances n=117(Avg)	Large Number of Appliances n=33 (Avg)	Total Number of Appliances n=333 (Avg)
Indoor Lighting	1,593 (16)	2,673 (32)	10,211 (87)	7,486 (227)	21,963 (66)
Outdoor lighting	215 (2)	209 (3)	498 (4)	275 (8)	1,197 (4)
Computer	386 (4)	580 (7)	2,267 (19)	3,335 (101)	6,568 (20)
Printer	212 (2)	253 (3)	719 (6)	493 (15)	1,677 (5)
Air conditioner	288 (3)	428 (5)	793 (7)	237 (7)	1,746 (5)
Refrigerator	80 (1)	91 (1)	189 (2)	134 (4)	494 (1)

The appliances' wattages and the number of hours that they are in use came from the survey, interviews with experts, and the literature review (Table 3.10).

Table 3.10: Appliances' wattages and number of hours in use per day

Appliances	Power [W]	Hours in use [h]	Energy use [Wh]
Indoor Lighting	40	9.5	380
Outdoor lighting	18	14	252
Computer	130	9.5	1,235
Printer	80	1	80
Air conditioner	900	9.5	8,550
Refrigerator	45	24	1,080

Appliances' penetration rate in the business categories

The total energy used in running the main appliances in each category was estimated in order to calculate their penetration rate in each business category. Penetration rate refers to the proportion of the total amount of energy used that is consumed by the appliance. Table 3.11 provides an overview of the energy use and penetration of the appliances.

As Table 3.11 indicates, air conditioners, followed by computers and then indoor lighting, are the major electricity consumers in the micro-, small- and medium business categories. In contrast, in the large category, air conditioners, followed by computers, and indoor lighting consume more energy.

Table 3.11: Energy use and penetration of appliances in the business groups

	Indoor Lighting	Outdoor lighting	Computer	Printer	Air conditioner	Refrigerator	Total
Micro businesses							
Energy use [Wh/year]	605,340	54,180	476,710	16,960	2,462,400	86,400	3,701,990
Penetration [%]	16	1.5	12.9	0.5	66.5	2.3	100
Small businesses							
Energy use [Wh/year]	1,015,740	52,668	716,300	20,240	3,659,400	98,280	5,562,628
Penetration [%]	18.3	0.9	12.9	0.4	65.8	1.80	100.
Medium businesses							
Energy use [Wh/year]	3,880,180	125,496	2,799,745	57,520	10,170,225	204,120	17,237,286
Penetration [%]	22.5	0.7	16.2	0.3	59	1.2	100
Large businesses							
Energy use [Wh/year]	2,844,680	69,300	4,118,725	39,440	4,052,700	144,720	11,269,565
Penetration [%]	25.2	0.6	36.5	0.3	36	1.3	100

3.6.2.3 Appliance penetration rates in Curaçao businesses

Figure 3.2 illustrates the average energy use breakdown in office buildings in Curaçao. As can be seen, air conditioners have the highest energy use (54%), followed by indoor lighting (22%) and computers (21.5%). This is in line with other energy use studies in office buildings in similar climatic conditions. Air conditioners are responsible for a major proportion of the total energy use (57%), followed by lighting (19%) and other appliances (24%) in Malaysian office buildings (Saidur, 2009).

Figure 3.2: Average energy use breakdown in office buildings in Curaçao

Table 3.12 presents typical percentages of energy use breakdown in office buildings in various countries (Saidur, 2009). These studies indicate that, as in our survey, air conditioners and lighting are the largest energy consumers.

Table 3.12: Energy use breakdown in various countries (Saidur, 2009)

Country	Penetration of energy use [%]		
	Air conditioner	Lighting	Other
Spain	52	33	15
Indonesia	51	14	26
USA	48	22	30
UK	55	17	28
Thailand	59	21	20
Saudi Arabia	50	20	30
Singapore	59	7	34

3.6.3 Awareness of the importance of saving energy in office buildings

The survey found that most of the respondents do switch off lights and other appliances when they are not in use. The majority of the participants (more than 80%) in all four business groups indicated that they are aware of the importance of saving energy. Micro-businesses are most aware of the importance of energy saving (91%), while the energy awareness of the other three groups is slightly lower as indicated in Table 3.13. The participants drew a stronger link between saving energy and saving money than saving energy and saving the environment. Approximately 90% of the respondents indicated that saving money is the reason they try to save energy, whereas only about 10% of the respondents said they saved energy for environmental reasons.

Table 3.13: Energy awareness

Business group	Energy awareness [%]
Micro	91.0
Small	84.3
Middle	82.9
Large	84.8
<i>Business group as a whole</i>	92

3.7 Introduction to energy use in hotel buildings in Curaçao

The tourism sector is an important sector for the economy of Curaçao, and it is one of the most important sources of financial income for the island. The hotel industry plays a key role in this sector. Here, hotel buildings are compared to other commercial buildings due to their multiple functional areas. Further, hotels in Curaçao vary greatly in terms of facilities, size, occupancy level, and standards, and their energy use has a great impact on electricity demand. Moreover, the energy use of hotel buildings varies depending on many factors such as the types of activities and services, cooling, lighting, refrigeration, telecommunications, water heating, and cooking (Önüt & Soner, 2006). Hotel buildings are among the most energy intensive of all buildings and, in recent times, the management of energy use in hotels has received considerable attention. Energy use is one of the main issues facing hotels, especially three-, four-, and five-star hotels (Ali, Mustafa, Al-Mashaqbah, Mashal, & Mohsen, 2008). Moreover, nearly all studies conclude that air conditioners dominate energy use in hotel buildings. For example, the study by Shiming and Burnett (2002) indicated that the contribution of air conditioners is 45%, followed by lighting (17%) and lifts and escalators (7%), with a miscellaneous category accounting for the remaining 31% of energy use. According to Tang et al. (2016), hot-water production, cooling, and space heating explain about three-quarters of the total energy use. The study by Wang (2012) also indicated that air conditioners are the main end use in hotels, responsible for almost half of

the total energy use. In contrast, Kresteniti (2017) concluded that lighting is the largest energy demand in Greek hotel buildings, (about 45% of the total energy used). This large lighting demand was attributed to the widespread use of high-wattage halogen lamps in those hotels. Moreover, there were no occupancy sensors or natural light control sensors in those hotels although some did have a magnetic card in their rooms for lighting control.

Notwithstanding the fact that there are many studies on energy use in hotel buildings, there is a lack of information on energy use in hotels in Curaçao. Therefore, a detailed survey of energy use in hotels in Curaçao has been carried out. The aim of this study was to gain insight into both the energy use in hotels and the appliances' penetration rates, and to estimate the energy savings potential. The research findings can be used to reduce the energy use in hotel buildings.

3.7.1 Energy use by hotels in Curaçao: Research approach

Curaçao has approximately 41 hotels, and 22 of them participated in this survey. All the approached hotels had joined this survey. The number of rooms within these hotels ranges from 17 to 341, and the average occupancy rate in 2017 was 75% ('Chata', 2018). The hotels that participated in this study were recruited by telephone to join the survey.

Site visits were organized to obtain the basic data related to energy use in the included hotels. During the site visits, the evaluator first collected information regarding the number and types of rooms. After that, information related to the number of appliances, their types, and their nominal power was collected. Furthermore, the technical employee of the hotels was approached to provide additional information on the appliances. Data on the appliances were not always available and, in these cases, data from online manuals were used. After the survey was completed, the collected data from each hotel were processed.

With the data collected from the interviews and information from relevant sources, the energy use and the energy savings potential were calculated.

3.7.2 Survey results and analysis

The hotels in Curaçao use three types of energy, namely electricity, gas, and diesel fuel. Diesel and gas are used for distinct purposes: diesel fuel is used for the backup generators, and gas is mostly used for cooking in the restaurants, although most of the furnaces and ovens in the surveyed hotels use electricity. Electricity dominates the overall energy use in hotels in Curaçao and therefore this study takes only electricity into account.

Figure 3.3 illustrates the average breakdown of the total energy use in 22 hotels in Curaçao, and Appendix 4 presents the energy breakdown in the individual hotels. According to the results of the field study, cooling, refrigeration, water heating, and lighting are the main energy consumers in hotels in Curaçao. As expected, cooling equipment is the predominant energy user in hotels due to the climate in Curaçao.

Cooling plant consumes about 41% of total electricity used in hotels. Refrigeration follows, using approximately 19.6% of the electricity consumption, followed by lighting (14.8%) and water heating (9.4%).

Figure 3.3: The average energy use breakdown

Notwithstanding that almost all the hotels use energy saving technologies to reduce the energy used in air conditioning, space cooling dominates the energy use in Curaçao's hotels. The survey results indicate that approximately 59.1% of the surveyed hotels utilize energy-efficient air conditioning systems, whereas only 27.3% still use the less-efficient conventional split air conditioner, and 27.3% have a central unit air conditioning system. Some of the hotels use both energy-efficient and conventional split air conditioning systems (see Table 3.14).

Table 3.14: Air conditioner systems in hotels in Curaçao

Hotels	Energy efficient air conditioner	Conventional split unit	Central unit
A	x		
B	x		
C	x		
D	x		
E	x		
F	x		
G	x		
H	x		
I		x	
J		x	
K		x	x
L	x	x	
M		x	
N		x	
O		x	x
P	x	x	
Q	x	x	x
R		x	x
S		x	x
T		x	x
U			x
V	x		
Total	12	12	7

Refrigeration is also a significant electricity load, in part because most hotels (68.2%) have refrigerators in the guest rooms. As in other international hotels (Placet et al., 2010), water heating also provides a significant load in the surveyed hotels. The survey found that hotels in Curaçao have several

types of water heating appliances (Table 3.15). Approximately 45.5% of the hotels have large, electric-powered conventional storage water heaters that supply heated water to multiple rooms, while 18.2% of the hotels have small individual electric storage water heaters for each room. About 4.6% of the hotels have small, tank less or instantaneous water heaters for each room. These latter water heaters provide significant cost savings, compared to a conventional storage water heater, since they heat water only on demand. Approximately 13.6% of the hotels have solar water heaters, and 9.6% have conventional gas water heaters. These solar water heaters have a hot water storage system, and they use solar thermal collectors to convert sunlight into heat and transfer it to water. About 13.6% of the surveyed hotels do not have warm-water installations for their guests.

Table 3.15: The availability of water heaters per hotel

No	Hotels	Small electric water heater	Large electric water heater	Solar water heater	Gas water heater	Tankless water heater
1	A	x				
2	B		x			
3	C	x				
4	D		x			
5	E		x			
6	F		x			
7	G			x		
8	H					
9	I					x
10	J					
11	K		x			
12	L			x		
13	M	x				
14	N					
15	O		x			
16	P		x			
17	Q	x	x			
18	R				x	
19	S		x			
20	T		x			
21	U				x	
22	V			x		
Total		4	10	3	2	1

The survey results indicate that the contribution of lighting to electricity demand in hotels is less than in the household sector and in office buildings. The main reason for this difference is that the hotel sector is more conscious about energy saving than the other two sectors. Furthermore, all the surveyed hotels have energy-efficient lighting systems. LED lamps (in 86.4% of hotels) and fluorescent energy-saving lamps (68.2%) are widely used. Nevertheless, incandescent light bulbs (40.9%), halogen lamps (22.7%), and TL fluorescent lamps (59.1%) are still used in many hotels, with many hotels using a combination of these types of lamps (Table 3.16).

Table 3.16: The type of lighting systems per hotel

No	Hotels	LED Lamps	Fluorescent energy saving lamps	TL-Fluorescent	Incandescent light bulbs	Halogen
1	A	x		x		
2	B	x	x			
3	C	x	x	x	x	x
4	D	x	x			
5	E	x		x	x	
6	F	x	x		x	
7	G	x	x	x		x
8	H		x			x
9	I	x				x
10	J	x		x	x	
11	K	x	x	x		
12	L	x				
13	M	x		x		
14	N		x	x	x	
15	O	x	x	x		
16	P	x	x	x	x	
17	Q		x			
18	R	x	x	x		
19	S	x	x		x	
20	T	x		x	x	
21	U	x	x	x	x	x
22	V	x	x			
Total		19	15	13	9	5

An important finding from our study is that almost all the hotels have installed equipment to reduce energy use. Besides energy-efficient lighting and air conditioners, 50% of the hotels use LED televisions (Table 3.17).

However, technologies such as occupancy sensors are less used in the surveyed hotels. From the results presented, it can be seen that only one hotel uses PV solar panels to generate electricity. The energy saving potentials will be discussed and estimated in Chapter 4.

Table 3.17: Type of televisions per hotel

No	Hotels	LED	LCD	Plasma
1	A	x		
2	B	x		
3	C	x		
4	D		x	
5	E	x		
6	F		x	
7	G	x		
8	H		x	
9	I		x	
10	J		x	
11	K	x		x
12	L		x	
13	M			x
14	N	x		x
15	O		x	
16	P		x	
17	Q	x		
18	R		x	
19	S	x		
20	T	x		
21	U	x	x	x
22	V		x	
<i>Total</i>		<i>11</i>	<i>11</i>	<i>4</i>

3.8 Energy use by supermarkets in Curaçao

In general, supermarkets are energy-intensive consumers (Klemick, Kopits, & Wolverton, 2015) due to the refrigeration required for the conservation of frozen and refrigerated products (Mylona, Kolokotroni, & Tassou, 2017). It is also notable that the energy intensity in supermarkets is growing. This is because many supermarkets are following the market trend towards

having prepared food areas (Clark, 2015). Supermarket buildings often also have large kitchens, restaurants, and bakeries.

Since there is a lack of information on energy use in supermarkets in Curaçao, a study into their energy use was conducted. The aim of this study was to gain insight into the energy use, the energy use breakdown, and the energy savings potential in supermarkets. The research findings will provide valuable input on structural options to reduce the energy use of supermarket buildings in Curaçao.

3.8.1 Energy use by supermarkets in Curaçao: Research approach

The nine respondents from supermarkets who participated in this study were recruited by telephone. The evaluator visited them to obtain the basic data related to their energy use. During these visits, the evaluator collected information regarding the number of appliances that are most frequently used in supermarkets, the types, and the nominal power of these appliances. After completing the survey, the collected data from each supermarket were processed. The energy use breakdown for each supermarket (Appendix 5) as well as the average energy use breakdown for supermarkets in Curaçao were calculated. With this information, the energy saving potential for the supermarkets has been estimated.

The energy use of each appliance is calculated by multiplying the wattage of each appliance by its estimated time in use. In the data presented, the 'miscellaneous' energy use is the difference between the calculated energy use of all the appliances and the actual energy use as recorded in the energy bills.

3.8.2 Energy use by supermarkets in Curaçao: Results and analysis

It is notable that TL-fluorescent, compact-fluorescent, and LED lamps are commonly used in the supermarkets, while energy inefficient lamps such as incandescent and halogen lamps are hardly used in this sector. All the supermarkets use closed refrigeration and freezer units (i.e. with doors),

which are more efficient than open freezers. This helps explain the surprisingly low contribution of refrigeration to energy use in supermarket buildings in Curaçao. The findings indicate that refrigeration, at 32%, is still the major contributor to electricity demand in supermarkets in Curaçao, followed by air conditioning (27%) and lighting (21%). Cooking and water heating together account for 10% of the total energy use and ICT for 7%. The, unexplained, 'miscellaneous' component amounts to only 3% of the total energy use. Figure 3.4 illustrates the average energy use breakdown for supermarkets in Curaçao.

Figure 3.4: Average energy use breakdown in supermarkets

The results of this study are in line with international studies. Several studies have demonstrated that refrigeration is the largest energy consumer in supermarket buildings (Arteconi & Polonra, 2017). According to Garcia and Coelho (2010), refrigeration represents approximately 30% of the total energy use in such buildings. Clark (2015) showed that refrigeration and heating, ventilation, and air conditioning (HVAC) are the major contributors to total energy use in supermarkets. Mylona et al. (2017) also stated that refrigeration is the largest energy consumer in supermarkets (60%), followed

by ventilation (12%), cooling (8%), lighting (8%), heating (6%), and other-electrical equipment (6%). Table 3.18 provides an overview of the energy use breakdown of supermarkets in various countries (Marugg, 2016).

Table 3.18: Energy use breakdown in supermarkets
(Marugg, 2016; Kwidama, 2018)

Appliances	South-Africa	Sweden	USA climate zone 5	United Kingdom	Curaçao
Refrigeration	45%	47%	62%	29%	32%
Lighting	8%	27%	15%	23%	21%
HVAC	18%	13%	8%	9%	27%
Water heating	12%	-	12%	-	10% and cooking
Ovens/bakery	16%	3%	-	12%	-
Office	-	-	1%	4%	7% (ICT)
Miscellaneous	1%	10%	2%	23%	3%

3.9 Conclusions from examination of energy use and energy behavior in Curaçao

After an in-depth literature study on energy use, energy behavior, and energy efficiency, four field studies were conducted in Curaçao to develop insights into the local energy use, energy behavior and energy efficiency :

- A survey in which 384 households in Curaçao participated
- A survey in which 333 representatives of office buildings participated
- A field study to examine the energy use and energy efficiency of 22 hotels
- A field study to examine energy use and energy efficiency of 9 supermarkets

In the survey in which 384 households participated, air conditioners (23%), lighting (28%), and refrigerators (22%) were identified as the appliances that use the most electrical energy in households. The survey also revealed a difference in use of energy efficiency appliances between income categories. About 42% of high-income households have energy-efficient appliances, whereas only 25% of middle-income households and 15% of low-income

households do. Cost savings, rather than environmental concerns, appear to be the most important driver of energy-saving behavior. The results also show that the households in Curaçao are unaware of many of the available energy-efficient options that they could apply to reduce their costs.

A much higher level of energy-saving awareness (at least 82.9%) was seen in the survey in which 333 representatives of offices participated. The highest level of energy awareness (91%) was found in the micro-business group (less than 5 employees). Here, as with households, costs rather than environmental concerns were the main driver of energy-saving behavior. The appliances that contribute most to the total energy use in office buildings are air conditioners (54%), indoor lighting (22%), and computers (21.5%).

According to the results of the field study in which the energy use and energy efficiency of 22 hotels in Curaçao were examined, cooling (41%), refrigeration (20%), water heating (15%), and lighting (15%) appeared to be the main energy consumers in this sector in Curaçao. As expected, cooling was the predominant energy user in hotels due to the climate in Curaçao. Almost all hotels make use of equipment to reduce their energy use. Besides energy-efficient lighting and air conditioners, 50% of the hotels have LED televisions. Nevertheless, other improvement opportunities to further reduce energy consumption still exist. For example, occupancy sensors are only used in a very limited number of hotels. Further, only one hotel makes use of PV solar panels to generate part of its own electricity.

Finally, a field study in which nine supermarkets participated revealed that in this sector, refrigeration was the largest energy user (32%), followed by air conditioners (27%), and lighting (10%). All the supermarkets in the field study used closed refrigerators and freezers, which are more efficient than open designs.

Consuming at least 73% of the total electrical energy used, one can conclude that air conditioners, lighting, and refrigerators are the major energy demanding appliances in households, hotels, and supermarkets. In office buildings, air conditioners and lighting use 77% of electricity consumption. These key loads are summarized in Table 3.19.

Table 3.19: Energy use breakdown in the surveyed sectors

Appliances	Households	Offices	Hotels	Supermarkets
Air conditioner	23%	54%	41%	28%
Lighting	28%	23%	15%	21%
Refrigerator	22%	1.4%	20%	32%
<i>Energy use share</i>	73%	78.4%	76%	81%

CHAPTER 4

Energy saving opportunities in Curaçao

This chapter addresses the third research question of this thesis: ‘What are the energy saving options and energy savings potential in the household-, the commercial-, and the industrial sectors in Curaçao?’ To provide an answer to this research question, an in-depth review was conducted of relevant scientific literature, reports, and documents. This was complemented with a number of field studies.

Section 4.1 first describes the principles of, and recent literature, on standby power consumption. This serves as a basis for a field study in Curaçao in which 20 households and three companies participated. This study aimed to assess the magnitude of standby power losses and to explore options for reducing standby power losses.

Section 4.2 describes the results of an extensive literature review on the requirements for energy efficient buildings in tropical climates. Based on this literature review, 16 building design principles that can contribute to comfort and energy saving in tropical areas were derived. These design principles were subsequently used in a field study involving 626 buildings to assess to what extent these design principles are applied in Curaçao and to deduce opportunities to increase energy efficiency and comfort in Curaçao.

Section 4.3 provides an overview of techniques to improve the energy efficiency of lighting systems. The options that are considered are: enhanced use of direct sunlight; efficient lighting systems; task-oriented lighting; relamping; maintenance and room color; delamping; improved controls; lenses, reflectors and diffusers; and smart, energy-efficient LED street lighting. This Section also provides a list of energy saving options for refrigerators, washing machines, air cooling systems, and office appliances. Besides lighting, as was seen in Chapter 3, also refrigerators and air conditioners are major consumers of energy in households, supermarkets, and hotels in Curaçao. Similarly, office appliances such as computers and printers are a major energy consumer in office buildings.

Section 4.4 provides an overview of the short-term energy saving potential in Curaçao, and for the longer-term until 2030.

Based on these sections, conclusions are drawn on the energy saving opportunities for Curaçao in Section 4.5.

4.1 The impact of standby power consumption

The standby power consumption of an individual appliance in the residential sector is small. However, the sum of the standby power consumption of all appliances becomes significant and can be up to 15% of the total electricity consumption in the residential sector (Clement, Pardon, Driesen, Leuven, & Electa, 2007; Meier, Lin, Liu, & Li, 2004; Sahin & Aydinalp Koksak, 2014). In addressing this issue, the aim of this section is to assess the magnitude of standby power losses in Curaçao and to explore possibilities to reduce these losses. This section is structured as follows. First, Section 4.1.1 introduces standby power, standby power losses, and the scale of standby power losses in several countries around the world. Section 4.1.2. outlines the research steps that have been followed to assess the magnitude of standby power losses in the residential sector in Curaçao, followed by a presentation of the research findings in Section 4.1.3. In Section 4.1.4. the opportunities for reducing standby power losses in the residential sector in Curaçao are discussed. This section ends with conclusions in Section 4.1.5.

4.1.1 Introduction to standby power and standby power losses

Standby power consumption, standby loss, vampire power, and leaking electricity all refer to the electricity consumption of appliances when they are not performing their primary function or are switched off (Meier, 2001). Standby power consumption was identified in the 1980s as a significant energy use, and it represents one of the largest end-uses in the residential sector worldwide (Fung, Aulenback, Ferguson, & Ugursal, 2003; Harrington & Foster, 2008). Standby power is related to the operational mode of an appliance. To clarify this relationship, Figure 4.1 illustrates the several operational modes of an appliance and the standby power associated with

these modes (Alan, Meier, & Lebot, 1999; Shuma-iwisi, 2009; Solanki, Mallela, & Zhou, 2013).

Figure 4.1: Block diagram of standby power

As can be seen in Figure 4.1, the appliance can first be in the plugged off mode or in the plugged on mode. An appliance does not consume standby power in the plugged off mode. When the appliance is in the plugged on mode, it can be in the switched on or the switched off mode. The switched

off mode is further subdivided into hard-off and soft-off modes. Appliances have a hard-off mode when the internal power supply circuit of the appliances is connected through a mechanical switch to the power source. In contrast, a soft-off mode refers to appliances where the mechanical switch connects the appliance's internal power supply circuit to an electronic circuit. Appliances do not consume standby power if they are in the hard-off mode; however, they do in the soft-off mode. This latter standby mode is labelled the passive standby mode if the appliance does not provide any function in this mode, but still consumes energy. Appliances in this mode can be powered up remotely (Alan et al., 1999; Clement et al., 2007).

Further, when an appliance is in the on-mode, it can be in active standby mode, passive standby mode or in an active/normal mode. In the active/normal mode, the appliance performs its main function, whereas in the active standby mode it consumes power but is not providing its main function (Alan et al., 1999). In this mode, appliances are waiting for a command to be activated. For example, an alarm system, an alarm clock, a computer router, and a garage door opener (Alan et al., 1999; Clement et al., 2007).

Almost all household electrical appliances and appliances with external power supplies consume standby power. In recent years, the number of appliances with standby power losses has increased rapidly.

Appliances that consume standby power are:

1. appliances that have no off switch;
2. appliances with a remote control;
3. appliances with LED status lights;
4. appliances with a display that includes LED status lights;
5. appliances with a memory keeping function
6. appliances with inefficient power supply; and
7. appliances with an external power supply, which is, in many cases, always connected to the electricity grid.

The electricity consumption of appliances in the standby mode is generally small, between 0.5 W and 10 W (Meier, 2001). Notwithstanding this small consumption, the sum of all the standby power consumptions represents a

considerable amount of power in the residential sector, with households' standby power consumption varying from 23 W to 112 W per home.

Standby power consumption can be up to 15% of the total residential electricity consumption (Clement et al., 2007; A. Meier et al., 2004; Sahin & Aydinalp Koksall, 2014). In addition, an estimation by the IEA showed that the annual global standby consumption in the residential sector was between 200 TWh and 400 TWh (Prudenzi et al., 2011), and is responsible for a considerable amount of CO₂ emissions. Table 4.1 summarizes the average standby power, the average standby power losses, and the fraction of the total electricity usage in the residential sector in different countries (Choi & Huh, 2005; Clement et al., 2007; Meier, Berkeley, & Nordman, 2007; Sahin & Aydinalp Koksall, 2014).

Table 4.1: Average national standby power, standby power losses, and fraction of total energy use (Sahin & Aydinalp Koksall, 2014)

Countries	Year of survey	Average standby power [W]	Standby Power losses [kWh]	Fraction of the total electricity usage in the residential sector [%]
Bulgaria	2002	33	789	-
Romania	2002	14	340	7.3
Hungary	2002	30	709	11.5
Italy	2002	57	472	15
Greece	2002	50	424	13.5
Portugal	2002	46	377	13.7
China	2004	29	100	4-16
Denmark	2005	67	120-980	2-18
New Zealand	2005	57±4	-	-
Australia	2005	85.3	-	10.3
Argentina	2007	23.1	-	7.7
Belgium	2007	40-50	274-435	8-12
USA/ California	2008	112	980	13
12 European countries	2009	39.8	305	11
Turkey	2011-2012	27	130	5

As already observed (Harrington & Foster, 2008), standby power represents one of the residential end-uses with the highest potential to save energy.

Furthermore, standby power can be reduced at a low cost (Meier et al., 2004). This is why several countries and non-governmental bodies have programs and policies to reduce standby power consumption, especially in the household sector.

Since no information was available about standby power losses in Curaçao, a study has been conducted to close this knowledge gap. The following subsections describe the research approach and the research findings of this study as well as the opportunities to reduce standby power losses in Curaçao.

4.1.2 Research approach to measure standby power losses in Curaçao

To estimate the magnitude of standby power losses in Curaçao's residential sector, a field study was conducted involving 20 households in Curaçao.

There are three methods for estimating standby losses (Meier, 2001; Tseleki, 2012):

1. new-product measurement;
2. bottom-up estimates approach; and
3. whole-household measurement.

New product measurement

New-product measurement involves visiting a store or factory and measuring the standby power of new appliances. The main advantage of this approach is that the measurements of many appliances can be taken in a short time. However, the measured standby power will not match the standby power in the residential and commercial sectors because the standby power of new appliances is often lower than older existing appliances.

The bottom-up estimates approach

The bottom-up approach is more appropriate when the appliance saturation and standby power data are available, and the average standby power corresponding to a country is then the estimated average standby power of the appliances multiplied by the appliances' saturation data (Meier, 2001; Sahin & Aydinalp Koksak, 2011). This method cannot be applied in Curaçao due to the lack of standby power information on the appliances found in Curaçao.

Whole-household measurement

The whole-household measurement approach consists of different actions, namely visiting a number of households; registering the type, model, and size of each appliance; measuring the standby power of the appliances in the households; and conducting a survey about the electricity consumption of the participants (Meier, 2001; Sahin & Aydinalp Koksak, 2014). The average standby power and the household standby power are calculated as follows (Sahin & Aydinalp Koksak, 2011):

The average standby power is the sum of the measured standby powers of the appliances divided by the number of appliances, as given in equation 4.1.

$$Y_i = \frac{\sum_{i=1}^n X_i}{n} \quad \text{Equation 4.1}$$

Where:

Y_i is the average standby power of appliance i

X is the standby power per appliance i

i is the type of appliance

n is the total number of appliance i

The average household standby power and the standby power losses are calculated in the same way. The average household standby power or

standby power losses is the total household standby power or standby power losses divided by the number of appliances, as given in Equation 4.2.

$$ST_i = \frac{\sum_{i=1}^n H}{n} \quad \text{Equation 4.2}$$

where:

ST_i is the average household standby power or standby power losses

H is the total standby power or standby power losses per household

The average standby power or standby power losses of a country is equal to the number of households multiplied by the average standby power or standby power losses of the households, as presented in Equation 4.3.

$$STC_i = ST_i * N \quad \text{Equation 4.3}$$

Where:

STC_i is the average standby power or standby power losses per country

N is the total number of households

The standby power consumption of an appliance is equal to its standby power multiplied by the standby time in hours, as given in the following equation:

$$X_c = x * t_{ST} \quad \text{Equation 4.4}$$

where:

X_c is the standby power consumption of an appliance

x is the standby power of an appliance

t_{ST} is the standby time in hours

A review of the available literature addressing standby power losses made clear that in most of the studies the 'bottom-up estimates approach' or the 'whole-household measurement' approach are applied (Sahin & Koksall, 2014; Lebot, Meier, Anglade, 2000; Sahin, Gugul, & Koksall, 2011). Given the shortcomings of both the new product measurement and the bottom-up estimate approach, in our Curaçao case study the 'whole-household measurement approach' will be applied to assess the standby power in the residential sector in Curaçao. The measurements in the Curaçao case study were carried out over a period of five months. In this period, the standby power losses of 250 devices in 20 households were measured. Nineteen households were owner occupied, and one was a rented apartment. The occupancy of these households varied from one to five persons, with an average of four people per household. Devices such as doorbells, security alarms, and garage door openers were excluded from the measurements since most houses in Curaçao do not have such devices. During all the standby power measurements, the appliances were either in the 'off mode' or in the 'on mode' but not performing their main task. In addition to the measurements, a survey consisting of 17 questions was carried out within the 20 households (see Appendix 6). The survey was conducted by a student of the faculty of engineering of the University of Curaçao. This survey was conducted to determine the electricity consumption behavior of the residents and the average time their appliances were in standby mode.

Standby power is often low and, therefore, the measurement of standby power requires a meter with sufficient resolution to take an accurate reading. A digital KPM1000 power meter was used in this study. This meter has a minimum power range of 750 MW and a maximum power range of 6 kW, and it can perform standby power measurements in compliance with IEC62301 (measurements of standby power for electrical appliances in the residential sector) with a resolution of 0.01 mW for a low range and 0.1 W for a high range. The accuracy of the measurements is $\pm 0.1\%$ of the reading ('User's manual digital power meter KPM1000', 2011).

4.1.3 Key findings from the measurements of standby power losses in Curaçao

Table 4.2 presents an overview of the results of the measurements of the standby power per household in Curaçao.

Table 4.2: Results of measurements of standby power per household in Curaçao

Household	Standby power [W]	Standby power losses per year [kWh/year]
Household 1	86.9	260.8
Household 2	28.5	40.2
Household 3	50.2	326.0
Household 4	15.3	95.2
Household 5	31.2	111.2
Household 6	25.5	46.3
Household 7	101.4	484.0
Household 8	53.1	311.1
Household 9	84.5	192.7
Household 10	28.2	65.1
Household 11	11.2	66.0
Household 12	66.3	401.9
Household 13	27.3	118.4
Household 14	76.4	295.0
Household 15	97.0	346.1
Household 16	25.8	146.9
Household 17	95.2	278.6
Household 18	36.7	252.5
Household 19	38.7	233.2
Household 20	26.0	186.4
<i>Total</i>	<i>1005.4</i>	<i>4257.5</i>
<i>Average per household</i>	<i>50.3</i>	<i>212.9</i>

The maximum standby power per household was calculated by summing the standby powers of all the appliances in that household (Table 4.2). It was

found that the standby power per surveyed household ranged from 11.2 W to 101.4 W, with an average maximum standby power of approximately 50.3 W per household. The study of Sahin and Aydinalp Koksali (2014) indicated that the average international standby power from several studies in the household sector is between 14 W and 112 W (Table 4.1). It is interesting to note that hardly any of the residents were aware of standby losses. The household with the smallest standby power (11.2 W) is a small household with few appliances. The results of this study were compared to those of several other studies and, in most cases, the results of our measurements were consistent with theirs. A notable exception concerned transformers. In many countries it is unusual to use transformers in the residential sector but, in Curaçao, almost all households have one or more transformers to step up or down the voltage, due to the different voltage levels 127V 50 Hz and 220V 50 Hz in the dwellings. Furthermore, the households have a mix of 120V 60 Hz and 220V 50 Hz appliances. Transformers are used in the Curaçao households when the appliance and supply voltages and frequency do not match. Nowadays, the use of transformers is decreasing because many modern electronic appliances can run on any voltage in the 100 – 240 V range and also with 50 or 60 HZ supplies.

The standby power of the appliances per household multiplied by the corresponding standby time per appliance provides the standby power consumption of a household.

From this survey, the minimum standby consumption of the households was found to be approximately 40.2 kWh/year, while the maximum was 484.0 kWh/year. The average standby power consumption of the measured households is about 212.9 kWh/year (Table 4.2). Average standby power losses per year from international studies range between 130 and 980 kWh (Table 4.1). Despite hardly any of the respondents being aware of standby power losses, the average standby power losses found from the survey is relatively low compared with other countries.

To determine the ratio between total energy use and standby power consumption in the household sector in Curaçao, it was first necessary to determine the total number of occupied households. In total, 69,255 households were connected to the electricity grid of Aquallectra in 2014,

including uninhabited dwellings. In 2011, about 7.7 % of the dwellings in Curaçao were uninhabited ('CBS', 2015). It was assumed that the percentage of uninhabited dwellings in 2014 remained about the same. Therefore, in this study, we considered 63,922 dwellings to be occupied.

The average standby power consumption of the measured households multiplied by the total number of households in Curaçao provides the total standby consumption of Curaçao, which is roughly: $63,922 \text{ households} * 212.9 \text{ kWh/year}$ is about 13,600 MWh/year.

To estimate the fraction of standby power consumption in the total household electricity consumption, the total standby power consumption of Curaçao in the residential sector is divided by the total household electricity consumption. In 2014, the total household electricity consumption was 271,738 MWh ('Aqualectra', 2015). This means that the total standby power consumption is about 5 % of the total annual household electricity consumption in Curaçao.

To estimate the average standby power of Curaçao, the average standby power of the households must be multiplied by the total households in Curaçao. The average standby power in Curaçao is about $50.3 \text{ W} * 63,922 \text{ dwellings}$ is 3.2 MW.

Table 4.3 gives an overview of the average standby power and the average standby power losses of several appliances in Curaçao.

Table 4.3: Results of measurements of average standby power losses

No	Product Category	Appliance	No	Average Standby Power [W]	Average Standby Power Losses [kWh/year]
1	Entertainment	TV decoder	23	13.4	90.5
		Television	28	0.6	4.9
		Radio	14	1.9	13.8
		DVD	8	0.6	6.3
		Blue ray player	1	0.3	0.0
		TV box	2	6.9	50.3
2	Communication	Computer	6	3.2	20.8
		Speaker	4	4.4	7.5
		Printer	15	1.0	14.1
		Router	10	3.5	17.2
		Modem	18	5.1	33.9
		Wireless Phone	9	2.0	16.3
		Phone charger	30	0.1	1.3
		Laptop charger	18	0.1	1.0
		Sunny web box	2	3.1	0.0
3	Cooking	Microwave	13	2.2	21.9
4	Food cooling	Refrigerator	1	12.4	43.5
		Freezer	4	0.2	0.8
5	Various	Transformer	5	12.2	51.5
		Air conditioner	12	3.2	24.0
		Washing machine	4	0.2	6.8
		Fan	7	0.3	6.7
		Game console	3	0.5	3.6
		IPad charger	4	0.1	0.0
		Control station "Click on/off"	1	3.0	26.4
		Receiver "Click on/off"	8	0.6	33.1
6	Total		250	81.1	496.2

The appliance in Curaçao with the highest average standby power losses is the TV decoder (90.5kWh/year), followed by the transformer (51.5kWh/year), and the TV-box (50.3kWh/year).

The results of this study are within the range of the results from international studies, although admittedly the range of the results in the international studies is quite large. These large variations are due to several reasons. According to Sahin, Gugul, & Koksai (2011), these differences are mainly caused by using different definitions and measurements of standby power. For example, some studies neglect small appliances and measure only large appliances. As a result, the estimated standby power will be lower than the results of other studies that include small appliances. The economic welfare of a country also plays an important role in the results of the studies. Furthermore, the standby power of new appliances is generally lower than the standby power of older appliances, and this effect also explains some of the differences. Another important reason for the differences is the standby awareness of consumers (Sahin et al., 2011).

4.1.4 Opportunities to reduce standby power consumption in Curaçao

The main options to reduce standby power losses are to change consumer behavior, technological innovations, and through government regulations (Clement et al., 2007).

Change consumer behavior

The behavioral option encompasses increasing consumer awareness of standby losses. According to Shuma-lwis and Gibbon (2009), consumer awareness can reduce standby power consumption by 25%.

Utility companies and/or governments can lead campaigns to encourage consumers to reduce their standby power. An easy and cost-effective way to reduce standby power consumption is to unplug appliances and devices when they are switched off, fully charged, or not performing their main functions. An electrical power bar is a useful option for easily unplugging home electronics, for instance TVs, computers, printers, DVD players, and

decoders when they are not being used. Another way to lower standby consumption is to purchase appliances with lower standby power. However, while some of these methods are inexpensive and easy to apply, it is not easy to motivate consumers to apply them because the achieved saving per appliance is quite low.

Technological innovations

The technical option covers the technological innovations that are applied to reduce standby power. Many manufacturers around the world have begun to produce appliances with lower standby power, using various methods such as by improving the efficiency of low-voltage transformers and using intelligent switches.

Another technological innovation is the intelligent electrical power bar, which can sense when appliances or devices are in standby mode or when they are in use. When it detects that the appliance or device is in standby mode, it automatically disconnects these appliances. In general, these bars are used to switch off units such as computers, printers, scanners, televisions, TV boxes, and DVD players. In Curaçao, these smart electrical power bars are still expensive and, as a consequence, the payback time is too long. For this reason, the penetration of these smart electrical power bars is very low in Curaçao.

Governmental regulations

The introduction of standby power labels helps consumers purchase an appliance with a lower standby power. The IEA launched the 1-Watt plan in 1999, with the proposition to reduce standby power. This plan limits the standby power of appliances and devices to a maximum of 1 W, and it has been successful. For example, the average standby consumption of a television has dropped from 5 W to 0.5 W ('*Tracking Clean Energy Progress*', 2013). By 2010, the participating countries banned the production of all appliances with a standby power above 1 W. Small countries could similarly choose to ban the import of all appliances with a standby power above 1 W.

In Curaçao, regulations are needed to encourage the importation of only 50 Hz appliances since this would reduce the standby power consumed by

widespread transformer use. Furthermore, the government should promote the purchase of appliances with an operating voltage that matches its intended location.

4.1.5 Conclusions: standby power losses in Curaçao

Most households have a maximum standby power load below 100 W, with an average maximum standby power of about 50.3 W per household, with an average standby energy consumption per measured dwelling of approximately 212.9 kWh per annum. Moreover, the results of this study indicated that the cumulative average standby power of all households in Curaçao is about 3.2 MW. The results also demonstrate that Curaçao's total residential standby power consumption is approximately 5% of its total annual residential electricity consumption. Furthermore, this section suggests several options to reduce standby power losses, namely: creating awareness about power supply losses, adopt technological innovations that reduce standby power supply, and the introduction of import regulations to prevent the importation of devices with a high standby power consumption.

4.2 Energy-efficient building designs for a tropical climate

The energy use in buildings in tropical climates is of great concern because many electro-mechanical systems are used to moderate the high humidity and high temperatures (Aflaki, Mahyuddin, Al-Cheikh Mahmoud, & Baharum, 2015), and also the artificial lights used for indoor illumination. To date, sustainable architecture for hot climate areas, including Curaçao, remains a relatively unexplored area ('Cairns Regional Council', 2011). Passive design strategies can improve buildings' indoor comfort, enhance energy efficiency in buildings, and minimize buildings' energy use (Rodriguez-Ubinas et al., 2014). Moreover, the design and construction of buildings can affect the environment, both directly and indirectly ('Cairns Regional Council', 2011):

1. directly, by constructing buildings and their infrastructure on green areas;
2. indirectly, through the extraction of resources to make building materials, the transportation of these materials, energy use once the building is functioning, and greenhouse emissions as a consequence of these activities.

Buildings in Curaçao were traditionally designed and constructed to take advantage of the sun and the wind (Brown, Eman, Halman, & Lauffer, 1974). However, in recent decades, in many cases, less attention has been given to aspects related to the sun and the wind in a building's design. This trend is also seen in other countries in the tropics. For instance, Tantasavasdi, Srebric, and Chen (2001) found that, in the past few years, passive cooling design elements have been missing from building designs. The natural indoor temperature consequently increases, and extra air conditioners or other electro-mechanical systems are then installed. According to Kitio, Butera, Adhikari, and Aste (2014), the current building process consists of three steps: architectural design, design of electro-mechanical systems, and construction. Passive design is absent from this process. "Passive design in the tropics means designing a building to make the most of natural light and cooling breezes, and using shading, orientation, and appropriate building materials to reduce heat gain and storage" ('Cairns Regional Council', 2011). A good passive design results in an energy-efficient and comfortable building. As a consequence, the capacity of mechanical ventilation systems can be reduced, mainly due to the reduction in a building's peak temperature during the day (Rattanongphisat & Rordprapat, 2014).

This section aims to identify the passive design features that could be used in the design and construction of buildings in Curaçao. To gain insight into how buildings are designed and constructed in Curaçao, 626 buildings were investigated.

4.2.1 Key tropical building design principles

The following paragraphs describe the most important design principles that should be taken into account in the design and construction process of a tropical building.

- *Building orientation*

Excessive solar radiation causes a building's indoor temperature to rise as a consequence of the solar heat infiltration. Therefore, the orientation of a building in the tropics is crucial (Jamaludin, Khamidi, Wahab, & Klufallah, 2014) because it can influence access to natural light, protection from

excessive solar radiation, and the extent of the prevailing winds on the façades of the building. The prevailing winds have two functions, namely to facilitate ventilation in a building as well as to ventilate the façades of the building ('Energy efficiency guidelines', 2013). Kitio et al. (2014) stated that the parts of a building where thermal comfort is an important requirement, such as a bedroom, should be situated to the side with the most wind. This is because the effect of mass-stored solar radiation in a building is still noticeable in the late evening. Conversely, other spaces such as restrooms and storage rooms can be located on the side with least wind. Moreover, Kitio et al. (2014) advised that most windows and the longest walls of a building should be out of direct sunlight. Nevertheless, the input of natural light and the maximum prevailing winds should be permitted.

For the longer axis of a building, the best orientation in Curaçao is perpendicular to the East-West direction. This ensures that the majority of the walls and windows obtain the maximum input of daylight and airflow. To minimize the negative effect of direct sunlight, the windows and the façades should be shaded. In Curaçao, it is recommended that overhangs, other types of shading, or vegetation are used to shield the windows and façades from the direct sun (see Figure 4.2).

Figure 4.2: A building designed with an overhang and vegetation (Hotel Floris Suite)

- *Natural ventilation*

Ventilation is the process of removing stale and replacing it with fresh air, either through mechanical systems or by natural methods (Liu, Meyer, & Hogan, 2010). When no mechanical systems are used in this process, it is referred to as natural ventilation or passive ventilation. Natural ventilation is important because it is an effective passive cooling design technique that reduces the need for energy to power mechanical ventilation systems (Tantasavadi et al., 2001; Wong et al., 2002). Two advantages of natural ventilation are that it reduces the energy use of the buildings and increases the thermal comfort in the building (Bastide, Lauret, Garde, & Boyer, 2006). Furthermore, natural ventilation is recommended as a way to encourage cross ventilation in buildings in the tropics. Effective cross ventilation in a building can be provided by placing windows in opposite walls. Figure 4.3

presents the layout of a dwelling where natural ventilation has been considered for the entire dwelling. To encourage cross-ventilation in the bedrooms, while maintaining privacy for the occupants, louver doors, or louvered windows above the doors, can be installed.

Figure 4.3: Natural ventilation in a house building design (Reardon & Clarke, 2013)

Limiting obstacles to airflow in a building is also recommended ('Cairns Regional Council', 2011; Reardon & Clarke, 2013). In addition, to stimulate mixing between fresh air and the air already in a building and to maximize airflow, the windows should not be directly in line (Kitio et al., 2014; 'Energy efficiency', 2013). Furthermore, Brown et al. (1974) recommended that the height of ventilation openings in dwellings should be at the occupant's upper body level, and that the building's interior walls should be thin and not hinder the airflow. Convective air movement or stack ventilation, which is based on temperature differences, can also improve cross-ventilation (Figure 4.4).

Low-level inlets and high-level outlets located on opposite sides of a building produce a “stack effect” (Diaz, 2016).

Figure 4.4 illustrates the principle of convective air movement. Openings on the upper level of the building let the warm air inside the building escape, while the cooler fresh air infiltrates through openings at a lower level in the building. Basically, this stack effect induces cool fresh air infiltration through openings at a lower level of the building and warm air removal through higher openings in the building (Reardon & Clarke, 2013).

Figure 4.4: Convective air movement or stack ventilation
(Reardon & Clarke, 2013)

The solar chimney is another design to encourage convective air movement (see Figure 4.5). This technique consists of a tall vertical chamber. During the day, the air inside this chamber is heated by solar radiation. This increases the difference in temperature between the incoming and out coming air. The natural convection therefore increases and this boosts the air circulation through the building.

Figure 4.5: Solar chimneys (Reardon & Clarke, 2013)

Another natural ventilation technique is to raise the building off the ground. This encourages fresh air supply from underneath, which cools the floor ('Cairns Regional Council', 2011; Brown et al, 1974). Figure 4.6 illustrates another ventilation technique, which is the use of ventilation blocks to enhance ventilation. Ventilation blocks are often used for ventilation purposes in buildings in Curaçao. It is important to note that the overhangs applied here are not deep enough to impede heat transmission to the interior of the house.

Figure 4.6: Example of open building blocks in an elevated house at Jan Thiel in Curaçao

Kitio et al. (2014) argued that, today, buildings should be designed to be integrated with the open air. This integration can provide a comfortable and healthy indoor environment, with a minimum use of energy for lighting, cooling, and ventilation. It is important to note that natural ventilation cannot entirely replace air conditioning units in hot climates. Consequently, Kitio et al. (2014) proposed dividing buildings into different areas — those where only natural ventilation would be used and air conditioned zones that needed additional air conditioning. Tantasavasdi et al. (2001) suggested several measures to increase natural ventilation, especially for houses. The most important of these are as follows:

- creating larger openings to serve as inlets and outlets;
- enabling free wind passage in buildings, by avoiding hinderances to the airflow; and
- designing buildings with more than one floor—the upper floors will receive better ventilation, and the ground floor can serve as a parking space and/or service area.

Mallick (1996) also argued that buildings with upper floors encourage natural ventilation.

Even if a building is designed with natural ventilation possibilities, ventilation can be drastically impeded, for instance by security grills and insect netting (Mallick, 1996).

- *Natural light*

The use of indirect natural light in buildings to illuminate their interior is crucial in any climate conditions. It reduces the energy use from artificial lighting as well as the interior thermal gains from this lighting. The orientation, shape, and surface openings of a building determine the extent of natural light ('Energy efficiency guidelines', 2013). Apart from windows and doors, indirect natural light can be acquired through skylights, light reflectors, and similar installations such as atria. Skylights and atria can provide plenty of light to a building's interior; however, they must be shaded or glazed in warm climates to restrict unwanted heat penetration. Other advantages of skylights and atria are that some of these installations have an opening at the top to allow hot air to escape ('Cairns Regional Council', 2011).

- *Windows*

Windows provide indirect natural light and direct airflow into most buildings. The size, material, and position of windows should be determined by the location and the façade orientations ('Energy Efficiency guidelines', 2013). It is important, especially in the tropics, that the windows are both exposed to and shaded from direct sunlight. There are several measures that can be used to minimize the heat input through windows such as tinted glass, other glazing technologies, overhangs, louvers, and reflective coatings ('Cairns Regional Council', 2011). Figure 4.7 depicts a building with exterior louvers fitted to both the windows and the door.

Figure 4.7: A building with exterior louvers for windows and doors (Hotel Floris Suite)

- *Roof ventilation*

The roof is the part of a building that receives the most solar radiation. The roof absorbs the heat from the sun and transmits it to the interior of the building. There are several ways to minimize the solar incidence on the roof, such as the following:

- I. Encourage natural ventilation of the space between the roof (insulated with downfacing Reflective Foil Insulation) and ceiling insulation (see Figure 4.8). Roof space ventilation reduces heat storage and minimizes the heat flow to the interior of a building. Trees provide shade to cool the roof and the incoming air. Create cross-ventilation to cool incoming heat from the roof and walls (Diaz, 2016).

Figure 4.8: Roof ventilation (Reardon & Clarke, 2013)

2. Use materials such as zinc and aluminum as the outside layer of a roof. Metal roofs with reflective layers permit quick cooling at night. However, this material has various disadvantages including glare from dazzling sunlight and disturbances caused by the noise of wind and rain. Furthermore, the lifecycle of zinc in the tropics is often shorter than that of other materials such as fiber-reinforced roofing materials and concrete.
3. Paint the roof a light color since this will lower the surface temperature, and less heat will consequently transmit to the building's interior.
4. Slope roofs towards the prevailing wind because this will encourage roof cooling by the prevailing winds.
5. Include roof insulation as this considerably reduces the heat input to the interior of the building (Kitio et al., 2014; Brown et al. 1974). The insulation can be mounted on the upper surface of the ceiling and/or under the roofing material.

6. Employ a double-roof shading technique to reduce the heat inside a building. The external roof serves as shade for the one below and protects it from direct sunlight (see Figure 4.9).

Figure 4.9: Double roof and shaded walls (Hotel Floris Suite)

7. Add a green roof (living roof) This is a roof whose outer layer is completely or partially covered by vegetation. The vegetation acts as shading for the roof.
8. Include ventilation openings between the ceiling and the roof to stimulate the escape of hot air through these openings. The hot air leaving through these openings will be replaced by cooler fresh air (see Figure 4.10).

Figure 4.10: Examples of new (architect ir. Tom Janga) and old architecture styles in Curaçao with ventilation provided above the ceiling.

- *Thermal mass*

In building design, thermal mass is defined as a measure of a building material's ability to absorb, store, and then retransmit heat. Building materials with a high thermal mass take a long time to heat up and to cool down (Liu et al., 2010). This means that the heat generated during high daytime temperatures is stored in a building's material and then flows out when the outside temperature drops at night (Rattanongphisat & Rordprapat, 2014). Therefore, lightweight materials with a low thermal mass, such as timber, are recommended as building materials in hot climates. Moreover, when materials with a high thermal mass, such as bricks and concrete, are used, the building needs to be shaded to prevent heat gain and heat storage.

- *Solar shading*

Heat transfer to the interior of a building occurs not only through the walls, but also through the windows and doors. Aflaki et al. (2015) recommended the use of shading elements at the top of openings to buildings (see Figure 4.11).

Figure 4.11: Shading elements at the top of the openings of a building at Winston Churchillweg

The use of light colors or reflective paints for external surfaces reduces the temperature at the surface of a building and hence the building's incidental heating (Latha, Darshana, & Venugopal, 2015; Rattanongphisat & Rordprapat, 2014). While internal insulation is another option to minimize the heat transmission to building interiors, solar shading is the most-used measure in the tropics to reduce the cooling load. For instance:

1. simple overhangs are the most-used methods in tropical climates. Overhangs are efficient for shading buildings;
2. vegetation on the outside of a building (see Figure 4.12) can also provide efficient shading for the building. However, it should not hinder natural ventilation. Moreover, planting can reduce the ground temperature and reduce the reflected heat (Aflaki et al., 2015; Cairns Regional Council, 2011; Latha et al., 2015); and

Figure 4.12: Vegetation as solar shading at Brakkeput in Curaçao

3. Besides exterior shading, interior shading such as vertical louvers and venetian blinds are other options. However, the best option is to keep the heat away from the building.

Figure 4.13 illustrates an energy-efficient dwelling in Curaçao designed by the famous Dutch architect and interior and product designer, Jan de Bouvrie.

Figure 4.13: Energy-efficient dwelling at Rif St Marie by architect Jan de Bouvrie

This dwelling has roof ventilation that reduces the heat stored in the interior of the dwelling. The doors and windows provide direct air flow through the dwelling. Furthermore, the walls, and all the doors and windows, are shaded from direct sunlight. The overhangs also have a cooling effect for the inflowing air. One negative aspect is that the dwelling has a dark-colored roof, where it would be better to have a light-colored one.

- *Outdoor and transition spaces*

The transitional or intermediate space between the inside and outside of a building can provide a shaded space for the building, and it has a cooling effect on the incoming air. There are many types of transition spaces that can be used in building design such as balconies, terraces, atriums, and

corridors. Figure 4.14 illustrates Fundashon Verriet, a health care institution in Curaçao with a transitional space. This building was designed by the famous Dutch furniture designer and architect, Gerrit Thomas Rietveld. The transitional space provides shading for the walls, windows, and doors and has a cooling effect on the entering air. Furthermore, the building has many windows, which encourages direct air flow into the building. The colors of the ceiling and floor are dark and again it would be better to use light colors.

Figure 4.14: Health care facility with transitional space at Sta Maria by architect Gerrit Rietveld

Design principles for tropical buildings

Table 4.4 summarizes important tropical building design principles, with the corresponding contribution to energy saving. All these principles contribute to both comfort and energy savings potential. The energy savings potential of applying the design principles is discussed in Section 4.9.

Table 4.4: Proposed tropical building design principles for Curaçao and their contribution to energy saving

No	Design principles	Result
1	Building orientation perpendicular to east-west direction	Energy used in both air conditioners and lighting will decrease
2	Natural ventilation	Energy used in air conditioners will decrease
3	Natural light	The energy used in lighting will decrease. In addition, the use of air conditioners can decrease due to the reduced heat produced by the lighting
4	Openings (windows and doors, ventilation blocks, etc.)	Energy used by both air conditioners and lighting will decrease
5	Roof ventilation	Energy used in air conditioners will decrease
6	Vegetation	Energy used in air conditioners will decrease
7	Light-colored roof	Energy used in air conditioners will decrease
8	Light-colored walls	Energy used in air conditioners will decrease
9	Roof insulation	Energy used in air conditioners will decrease
10	Wall insulation	Energy used in air conditioners will decrease
11	Double-roof shading	Energy used in air conditioners will decrease
12	Green roof	Energy used in air conditioners will decrease
13	Sloping roof towards prevailing wind	Energy used in air conditioners will decrease
14	Thermal mass	Energy used in air conditioners will decrease
15	Solar shading	Energy used in air conditioners will decrease
16	Outdoor and transition spaces	Energy used in air conditioners will decrease

4.2.2 A field study of the application of passive design principles in Curaçao: research approach

To gain insight into how buildings in Curaçao are designed and constructed, a field study was carried out in different neighborhoods in Curaçao. These neighborhoods were Schelpwijk, Gosie weg, Tera Kòrá, Soto, Brievengat, Caracasbaai weg, Sta. Rosa weg, Saliña, Punda, Otrobanda, Ronde Klip, Cas Kòrá, Bonam, Semikok, Sta. Rosa, Montaña, Fuik, Cas Grandi, Janthiel, Brakkeput, Rooi Catootje, Soemboe, Lagun, Barber, Knip, Souax, Gato, and Westpunt. The study included 626 buildings (315 residential buildings and 311 commercial buildings). Google earth, Google map, and Google street view were also used in this study. Google earth and Google map were used to gain insight into the colors of the roofs of the buildings and Google street view was used to get insight into the colors of their walls.

The aim of this investigation was to examine the extent to which passive design principles are incorporated in the design and construction process of the buildings. This investigation considered the following key elements of passive design:

1. the orientation of the buildings;
2. the materials from which the buildings are constructed;
3. insulation of windows;
4. solar shading;
5. roof material;
6. roof color;
7. roof ventilation;
8. wall color;
9. transition space;
10. floor levels; and
11. building elevation.

Note that temporary shades, such as awnings, are ignored.

4.2.3 A field study on the application of passive design principles in Curaçao: results and analysis

The 626 buildings included in this field study were evaluated on the application of the passive design principles that were deduced in Section 4.2.1.

Orientation of the buildings

The results reveal that the orientation of 83.5% of residential buildings and 81.7% of commerce buildings encouraged both daylight and airflow. These results are in line with the study by Brown et al. (1974).

Building materials

Almost all the buildings in Curaçao are built from concrete or cinder blocks (a hollow rectangular building block). About 98.7% of the examined commercial buildings are made of concrete or cinder blocks, while approximately 1.3% are constructed with timber or other materials (see Figure 4.15).

Figure 4.15: Building materials used in the commercial sector in Curaçao

The results also indicate that roughly 97.1% of the investigated residential buildings are built from concrete or cinder blocks, while 1.9% of them are built of timber, and about 1% are constructed using both types of material (see Figure 4.16). It is important to note that all the examined residential buildings built of timber belong to low-income households.

Figure 4.16: Building materials used in the residential sector in Curaçao

Insulating windows

Roughly 65.7% of the windows in residential buildings and 68.2% of those in commercial buildings are tinted or glazed. However, only 9.5% of the low-income residential buildings have tinted or glazed windows.

Solar shading of walls

About 93.3% of the residential buildings have some form of solar shading, mostly in the form of overhanging elements

.

Figure 4.17: A dwelling with a typical small overhang at Brakkeput in Curaçao

This is a higher proportion than with commercial buildings, where about 77.8% have similar shading. It is important to note that, in most cases, the overhangs are small, as depicted in Figure 4.17, and therefore do not provide shade for the entire wall.

Roof material

Fiber-reinforced roofing materials is the most-used roofing material (73.3%) in the investigated residential buildings, followed by zinc/aluminum (12.7%), roof tiles (5.7%), concrete (3.2%), and shingles (0.6%). About 4.5% of the examined residential buildings had a flat roof and it was not possible to identify the roofing. Figure 4.18 illustrates the roof materials used in the residential sector in Curaçao.

Figure 4.18: Roofing materials in the residential sector in Curaçao

About 26% of the examined commercial buildings had fiber-reinforced roofing materials, followed by roof tiles (9%), shingles (5.1%), and zinc/aluminum (2.3%). The remaining 53% of the investigated commercial buildings had flat roofs of unknown material. Figure 4.19 presents the roof materials used in the commercial sector in Curaçao. It is likely that most of the flat roofs are made of concrete since this form of construction reduces the risks from storms and high winds. Another reason for including a concrete flat roof is that it makes it easier to expand the building in the future with one or more upper levels. A major disadvantage of these concrete roofs is that they often have a black bitumen layer which absorbs more heat than lighter colored roofs. Unfortunately, this study was not able to study the flat roofs to more definitely identify their construction.

Figure 4.19: Roofing materials used in the commercial sector in Curaçao

A notable observation is illustrated in Figure 4.20. That is, that due to a lack of maintenance, roofs can become discolored with a black layer due to pollution. As a consequence, the roof will absorb more heat, which will be transmitted to the interior of the building. This phenomenon was often observed during this investigation.

Figure 4.20: Roof with a black layer due to pollution

Roof paint

The results show that approximately 42% of the roofs of the residential dwellings are a light color, while about 58% of the roofs have a dark color. The proportions are very similar in the commercial sector with around 41% of the roofs being a light color, and about 59% having a dark color. Here Google Earth was used to check the color of the flat roofs.

Roof ventilation

For the investigated residential and commercial buildings, about 62.9% and 31.6% respectively had some roof ventilation, however the roof ventilation of almost all the buildings was very limited. Only 22.9% of the investigated low-income residential buildings had roof ventilation.

Wall color

The study found that 61% of residential buildings have a light wall color, while 39% have a dark color. In the commercial sector, 46% of the commercial buildings had light walls and in 54% the walls were a dark color.

Transition spaces

Almost all the investigated houses had at least one transition space or balcony (91%), while 50.5% of the investigated commercial buildings had transition spaces. It is notable that only 23.5% of low-income residential buildings had transition spaces.

Floor levels

Most of the buildings in Curaçao are single-story: approximately 84% of the residential buildings and about 72% of the commercial buildings have only one floor.

Elevated buildings

In the field study, only two residential buildings were found in which a part of the building was elevated.

Double roof

The study found that eight commercial buildings were found with a double roof.

Key concerns with respect to the application of passive design principles in Curaçao

Based on the findings of this field study, the conclusion is justified that the use of high thermal-mass building materials, the dark color of many roofs, poorly insulated windows, particularly in low-income residential buildings, a lack of maintenance to remove black discoloration on roofs, a lack of transition spaces in low-income dwellings, as well as in commercial buildings, all have a negative effect on the internal comfort and the potential to reduce the energy consumed by air conditioners. Although most of the walls have solar shading, in most cases this shading is too small and insufficient to shade the entire wall of the building. This insufficiency was also the case with roof ventilation: although several dwellings are designed with roof ventilation, the ventilation openings are often too small to make a real difference.

It is evident that most of the dwellings of the poorest citizens are particularly deficient when it comes to passive design features. The walls are often made of timber, and the roof material is often zinc. According to Brown et al. (1974), the indoor temperature of these types of houses will be extremely high during the day. However, in the evening, this is one of the most cooling constructions, because in the evening the warm air flows out very easily and there is little thermal mass.

More than half of the commercial buildings are built close together. This is because of the scarcity of land in commercial areas. This will hinder the use of natural effects such as cooling airflows and natural light. In contrast, residential buildings generally have adequate spacing.

As discussed in Section 4.2.1, there are several passive cooling strategies to create a cooler building and reduce energy use in buildings. The key to designing a cooler building is to minimize heat gain and to harness natural ventilation. Based on the results of this study, the most important strategies, which can be applied in Curaçao to create cooler buildings and through this reduce energy use are summarized below:

1. use low thermal-mass material in the buildings to reduce the heat gain. For example, avoid or minimize the use of high thermal-mass materials in sleeping areas;
2. facilitate natural ventilation as much as possible in all rooms of a building through an effective layout design;
3. use light colors for both the walls and the roofs of buildings. Dark colors absorb heat and retain it longer than light colors;
4. shade the buildings and keep the heat of the sun away from the building. Overhangs, sunshades, trees, and plants are good options to shade buildings in Curaçao. The overhangs must be of an adequate size to shield the building from the sun.;
5. install insulation in the walls and the roof of a building. Insulation reduces heat transfer through walls and ceilings and also reduces heat gain; and
6. create roof spaces with adequate natural ventilation. These spaces act as buffer zones and reduce heat gain and heat transfer through the building;

To achieve the potential benefits that can be realized through tropical building design principles, it is highly recommended to introduce passive building energy codes in Curaçao.

4.3 Techniques for improving the energy efficiency of the most-commonly used appliances

In this section, the most-commonly used appliances and the corresponding saving opportunities will be described.

4.3.1 Improving the energy efficiency of lighting systems

In this section, techniques for improving the efficiency of lighting systems will be described.

- *Using Daylight*

Consumers can take advantage of daylight by integrating daylight into the building's design. The main disadvantage of using daylight is the associated heat transmission into a building's interior. There are various methods that can be used to eliminate or minimize these disadvantages, including the following (Kreith & Goswani, 2008):

1. the installation of louvers;
2. external solar screens;
3. a reflective film with a high percentage transmission of visible light for a clear appearance and a low shading coefficient to block some of the heat; and
4. building overhangs.

- *Task-oriented lighting*

Task-oriented lighting is an approach where a lighting system is designed to specifically illuminate one or more work area. Areas such as closets, corridors, and storage areas need and are provided with less illumination than other areas (Caperhart, Turner, & Kennedy, 2008; Kreith & Goswani, 2008).

- *Relamping*

Relamping refers to the replacement of existing lamps, fixtures, and ballasts with newer, lower-wattage, or more energy-efficient models, such as LEDs. Relamping contributes significantly to energy savings in residential and non-residential sectors. The energy use of air conditioners will also decrease due to the smaller amount of heat produced by the lamps (Caperhart et al., 2008; Kreith & Goswani, 2008).

- *Lighting maintenance and room color*

A light room color increases the illumination in an area. Lighting maintenance is beneficial because its contribution to lighting efficiency can be significant. For instance, dust and insects on bulbs can considerably decrease the illumination provided. In some situations, dirt and dust decrease the lighting levels by up to 30%. Moreover, they reduce the lifetime of the lamp due to the increased heat in the fixture. A typical strategy for replacing lamps is often called spot-relamping, meaning that a lamp will only be replaced when it has burnt out. The main disadvantages of spot-relamping are that it is more labor intensive per lamp, and it results in less efficient lighting than group relamping. Group relamping involves replacing a set of lamps at a scheduled time, and it provides higher light levels and an excellent quality of light because the lamps will be replaced before their output has decreased significantly, and the likelihood of mixing different lamps with different color temperatures will be minimal (Caperhart et al., 2008; Kreith & Goswani, 2008).

- *Delamping*

Delamping consists of the removal of lamps from areas where lighting is excessive for the requirements of the space. Delamping is a good opportunity to reduce energy use (Caperhart et al., 2008; Kreith & Goswani, 2008).

- *Improved controls*

Lighting controls can control lighting to when and where it is needed. They can contribute significantly to energy saving. In this subsection, the most-used lighting controls will be discussed (Caperhart et al., 2008; Kreith & Goswani, 2008)):

- a. The standard switch*

The standard switch was the first energy conservation device. The main disadvantage of this type of switch is that, in many cases, the occupants either forget to turn off the light or are not aware that they should turn it off when it is not needed. Standard switches need to be installed in such a way that they can be easily used, otherwise occupants are more likely to leave the lamps on. Furthermore, the switches can contribute to energy saving if they are easy to use. Energy efficiency can also be improved by redesigning poorly designed lighting systems by adding additional switching. Additional switches can be installed in large areas to switch off the lights in specific parts of the area when not in use (Kreith & Goswani, 2008).

- b. Time clocks*

Time clocks can be used to control lighting systems with a fixed operating schedule. These clocks are available in electronic and mechanical forms. Electronic time clocks without a battery backup will lose their information after a power failure (Kreith & Goswani, 2008).

- c. Photocells*

Photocells can be installed to control lighting systems, and they can control several systems at the same time. Photocells automatically turn on lighting systems when it becomes dark, and they turn them off when daylight is available (Caperhart et al., 2008). In general, photocells are used to control exterior lighting systems. A combination of photoelectric switches and timers can also be used for exterior lighting (Kreith & Goswani, 2008).

d. Lumen depreciation compensation

As mentioned previously, lighting systems are frequently over designed. Lumen depreciation compensation techniques control light levels with a photo sensor. This sensor detects the level of light and sends a low-voltage signal to an electronic dimming ballast to adjust the light level. Lumen depreciation compensation techniques improve energy efficiency because less power is needed for the new light level (Kreith & Goswami, 2008).

e. Daylight dimming

Daylight dimming also provides energy savings. In locations adjacent to windows, energy savings can be up to 30%. Daylight dimming provides a nearly constant level of work surface brightness by adjusting to variable levels of daylight illumination (Kreith & Goswami, 2008).

f. Occupancy sensors

Occupancy sensors automatically turn off lights in areas that are not occupied and turn on a light when motion is detected, and then turn it off when there is no motion in the area. Furthermore, both the sensitivity and the time delay of most of these sensors are adjustable. To improve sensor reliability and minimize false switching, dual-technology sensors can be used. They are a combination of ultrasonic and passive infrared detectors. According to Hordesky and Micheal (2004), the savings obtained by occupancy sensors are dependent on the area within which they are installed. There are savings of between 20% and 50% in office areas, 45% to 65% in meeting rooms, 30% to 40% in corridors, and 50% to 75% in warehouse storage areas. However, occupancy sensors can affect lamp life, since these sensors may cause rapid on–off switching. Various laboratory tests have demonstrated that if lamps are turned off and on every three hours, then their operational lifetime can be shortened by 25%. Hordesky and Micheal (2004) stated that although occupancy sensors may cause lamp life to be reduced, the actual on-time of the lamp also decreases and, in many cases, the time until relamping will not change. The longer the lights are off, the longer the lamps will last. Occupancy sensors will particularly save energy in areas that are not used for long periods of time. Therefore, they are more appropriate for a room that is occupied once every three hours than for one that is occupied once every three minutes.

- *Lenses, Reflectors, and Diffusers*

The illuminance of many existing lighting systems in residential and non-residential sectors is far below optimal. As mentioned earlier, this is to an extent the result of task changes, poor design, and/or old lamps. Adding lenses, diffusers, or reflectors can be helpful, and the light distribution pattern can often be improved by adding these to existing lighting fixtures. This can avoid the unnecessary use of extra lamps (Caperhart et al., 2008; Kreith & Goswani, 2008).

- *Smart and energy-efficient LED street lighting*

Smart and energy-efficient LED street lighting systems switch lights on when they are needed, and off when not needed. These intelligent systems consist of an LED lamp, a motion sensor, a brightness sensor, and a communication network (Fujii, Yoshiura, Takita, & Ohta, 2013). They can reduce the energy use of street lighting systems by 75% (ESTCP, 2013). According to Fujii et al. (2013), it is difficult to distinguish between smart systems and conventional systems in operational terms because lights will be turned on before pedestrians and car drivers are on the road. Approximately 5% of the street lighting systems in Curaçao are LED lamps ("OW", 2018). Thus, there is considerable room for further take up. In this study, it is estimated that the savings would be about 4 GWh per annum if 50% of the street lighting systems were replaced by LED lamps.

4.3.2 Improving energy efficiency of refrigerators

Chapter 3 has demonstrated that the refrigerator is one of the most energy consuming devices in the residential sector, in supermarkets, and in hotels in Curaçao. Nowadays, there are a range of energy-efficient refrigerators and freezers on the market, with better insulation and more efficient compressors through which the yearly energy use can be significantly reduced. According to Kreith and Goswani (2008), the following additional savings can be obtained in use:

- I. if the refrigerator is placed in a cool location and the coils are frequently cleaned;

2. when the door of the refrigerator is open, the temperature inside will start to rise, and energy will be used to cool it back down. Reducing the number of times the door is opened and the amount of time that the door remains open can save energy;
3. another way in which to save energy is to increase the temperature setting of the refrigerator; and
4. precooling foods to ambient temperature before placing them in the refrigerator can also lead to energy savings. If hot foods are placed in the refrigerator, the temperature in the refrigerator will rise and require extra energy to lower it again.

4.3.3 Improving energy efficiency of washing machines

Most of the energy used in the washing of clothes is for heating the water; the energy use of washing machines is mainly determined by the selected temperature. In addition, the load size and the energy efficiency of the washing machines also influence the energy use of the machines. According to Pakula and Stamminger (2015), savings of up to 50% in energy and water can be obtained. This can be realized besides the technological improvements of the machines, by changing consumer behavior towards using low-temperature wash programs, and reducing wash cycles per household (Pakula & Stamminger, 2015).

4.3.4 Improving energy efficiency of air conditioners

In this section, various energy-efficient air conditioners are described.

- *Inverter air conditioner*

Today, there is a new, energy-efficient air conditioner on the market: the inverter air conditioner. This type of air conditioner adjusts its cooling or heating capacity by adapting the frequency of the compressor's power supply. By regulating the speed of the compressor to control the refrigerant flow rate, it consumes less energy. This type of air conditioner precisely controls the temperature: when the set temperature is reached, the capacity of the unit is modified to ensure indoor temperature stability. In contrast, conventional air conditioners have a fixed cooling or heating capacity and,

therefore, the indoor temperature can be regulated only by starting or stopping the units. As a result, the indoor temperature fluctuates, and the energy use increases sharply when the compressor restarts. These make the inverter air conditioner more energy-efficient and comfortable than the conventional air conditioner.

- *Renewable energy alternative: seawater air conditioning*

The seawater air conditioning (SWAC) process is conceptually quite simple: it uses cold water from the deep sea or a deep lake to cool buildings. Unlike conventional air conditioning systems that use refrigerants and energy-intensive refrigeration systems for space cooling applications, SWAC does not use energy-intensive refrigeration systems and uses cold seawater instead of refrigerants.

The SWAC process can easily be adapted to the conventional chilled-water, air-conditioning system (War, 2011). The main components of SWAC are as follows:

1. a deep-sea water-supply system, including intake pipes, outflow pipes, and pumps;
2. a heat exchanger facility or cooling station; and
3. a closed, freshwater distribution system, which consists of distribution pipes and pumps.

The basic concept of SWAC involves taking advantage of the cold water from the lower parts of a deep sea or a deep lake. The cold seawater flows through a heat exchanger, extracting heat from the closed-loop freshwater, thereby cooling it down. Figure 4.21 illustrates the SWAC system.

Figure 4.21: The Sea Water Air Conditioning System (SWAC), (War, 2011)

- *Renewable energy alternative—ocean water assisted cooling*

The basic concept of the ocean water assisted cooling (OWAC) system is very similar to the SWAC system described above. The main difference between them is that OWAC does not use cold, deep-sea water, but seawater at approximately 28°C. The basic components of OWAC are the seawater supply system, the OWAC cooling system, and the freshwater distribution system. Since the OWAC process is still new, a full description has yet to be published.

The operating costs and the overall lifecycle costs of OWAC are extremely low. Furthermore, an OWAC plant delivers three times more cooling capacity than a conventional cooling system for a similar amount of energy use (omega-engineer.com, 2018).

- *Air conditioning opportunities: summary*

The SWAC and OWAC processes are technically viable and economically feasible, and both can be used for building and district cooling. Furthermore, the SWAC and OWAC systems both provide environmental benefits

(omega-engineer.com, 2018; War, 2011). A constraint is that the buildings and districts must be located close to the sea.

The adoption of the more efficient inverter-based units may be more widely applicable and should be considered, especially when replacing units that have reached the end of their life.

Besides the use of energy-efficient air conditioners, there are various actions that can be taken to save energy, including the following:

- turning off air conditioners when the area is not in use;
- setting the temperature at a higher but still comfortable temperature, between 22°C and 24°C;
- reducing heat transmission from outside to a building's interior;
- turning off appliances that are not in use, since they emit heat to the cooled area, resulting in air conditioners having to work harder;
- cleaning and maintaining the air conditioner regularly; and
- ensuring that the cool air does not escape to other areas and/or to the outside.

4.3.5 Improving energy efficiency of office appliances

A wide range of appliances that are used in the residential sector are also used in other sectors. This section lists actions to reduce the energy use of office appliances that were not discussed in the previous section:

- powering down computers when they are not in use;
- buying a laptop instead of a desktop, if practical, since the former consumes five times less electricity;
- purchasing an LED instead of an LCD screen for a desktop;
- activating the sleep, standby, or hibernate settings of computers, since screensavers do not reduce energy use, rather it is the standby setting that puts a computer into the energy-saving mode, where it uses little power, and hibernate saves the workspace (all open windows) and then turns the computer off, while sleep is more complicated because it means different things on different computers;

- turning off appliances to avoid ‘phantom’ loads—many appliances continue to draw a small amount of power when they are switched off;
- consolidating printers and scanners (reducing the numbers of printers and scanners); and
- minimizing printing.

4.4 A global estimation of the energy savings potential in Curaçao

Based on the findings described in Chapters 3 and 4, a global estimation of the energy savings potential for the island of Curaçao is now made.

- *Focus on the most-used energy intensive devices and sectors*

Given the share of energy use and the large energy savings potential of air conditioners, lighting systems, and refrigerators and freezers, these appliances were chosen to estimate the energy saving potential in Curaçao. As such, small appliances were not taken into account in this estimation of the energy savings potential for Curaçao. Sections 3.5.3. and 3.6.2 showed that:

- Air conditioners are responsible for approximately 53.9% of the total energy use in office buildings, 41% in hotels, 28% in supermarkets, and 22.7% in the residential sector in Curaçao.
- Lighting systems account for about 28% of the energy use in the residential sector, 24% in supermarkets, 23% in office buildings, and 15% in hotels.
- Refrigerators and freezers consume around 32% of the total energy in supermarkets, 22.1% in the residential sector, 20% in hotels, and 1.4% in office buildings.

In estimating the energy efficiency potential in the various categories, we make the following assumptions:

- the energy use of hotels per year represents the energy used in the export industry category. This is because, the hotels are the largest export industries in Curaçao;
- the energy use of the commercial sector per year is represented by the energy use of office buildings; and
- the energy use of the standard industries per year is represented by the energy use in the supermarkets.

Apart from the above-mentioned largest electricity categories in Curaçao, we also include the street lighting category in the estimation of the potential energy savings. In this estimation, we neglect the effect of the two smallest categories, namely hospitals and the ‘replaced import industry’, due to their relatively small magnitudes. However, the share of energy use of air conditioners, refrigerators, and lighting systems is also high in these sectors.

- *Energy savings potential due to stimulating energy savings behavior*

The estimation of the energy savings potential also includes savings due to changing consumers’ energy savings behavior, particularly reducing standby power use. The contribution of standby power in the residential sector of Curaçao is approximately 5% of the total energy use in this sector but this could be reduced through energy savings behavior. The European Environment Agency (EEA) argues that there is a growing body of evidence in the academic literature that there is a potential of up to 20% energy savings through various measures targeting behavior (EEA, 5-2013) as shown in Table 4.5.

Table 4.5: Savings obtained through measures targeting behavior (EEA, 5-2013).

No	Interventions	Savings
1	Energy audits	5-20%
2	Community-based initiatives	5-20%
3	Feedback	5-15%
4	Feedback and target settings	5-15%
5	Indirect feedback (for instance enhanced billing)	2-10%
6	Direct feedback (including smart meters)	5-15%
7	Combination of interventions (more than one)	5-20%

It is important to note that, in many countries, the savings achieved dropped after the interventions ended. One of the reasons of this drop was that the participants only received incentives during the intervention period and their energy use was only monitored during the intervention period. Another important aspect is the rebound effect, which is also called substitution or the take-back effect. This terminology refers to the effects that lower costs of energy services, for instance due to energy-efficiency improvements, have on the behavior of consumers (Abrahamse, 2007; 'Achieve energy efficiency', 2013). In the EEA report (EEA, 5-2013), three types of rebound effect are identified. Table 4.6 presents them and their corresponding explanations (EEA, 5-2013).

Table 4.6: Three types of rebound effect (EEA, 5-2013)

No	Type	Impact
1	Direct	Where increased energy efficiency and associated cost reductions for a product/service result in an increased consumption because it is cheaper.
2	Indirect	Where savings from efficiency cost reductions enable more income to be spent on other products and services.
3	Economy-wide	Where greater efficiency drives economic productivity overall, resulting in more economic growth, and hence additional consumption at the macroeconomic level.

We assume that a reduction of at least 5% in the total energy use in Curaçao is possible through consumers' energy saving behavior. Further, the standby power losses will be drastically reduced in the future due to new technologies and by increased standby power losses awareness, and through governmental regulations. As explained in Section 4.1.3, the total standby power consumption is about 5 % of the total annual household electricity consumption in Curaçao.

- *Energy savings potential due to the application of passive building design principles*

Section 4.2 showed that the application of passive building design principles would reduce energy consumption, both in the residential and in the commercial sector. These improvements will have a considerable influence on the energy use for cooling. The energy-efficiency guidelines for office buildings in tropical climates (OAS, 2013) provide indications of the energy savings that can be achieved by introducing building energy efficiency improvements. These savings are as follows:

- 1) solar protection can reduce the cooling demand by approximately 17%, while the lighting demand can be decreased by about 8%;
- 2) double glazing with air gap can reduce the cooling demand by about 4% compared to single glazing, and a cooling demand reduction of approximately 10% can be achieved by using special glazing;

- 3) roof shading techniques contribute to around a 16% reduction in cooling demand; and
- 4) about a 5% cooling demand reduction can be obtained by using building materials with a medium thermal-mass.

Based on the above-mentioned energy savings, we assume that the effect of building improvements on the cooling load will be about 10% for both residential and non-residential sectors. We further assume that building energy efficiency improvements will lead to about a 1% reduction in the required energy for lighting systems in the non-residential sector. The potential energy savings from household lighting systems due to building energy efficiency improvements is neglected in this study. This is because, generally, the dwellings in Curaçao are built in such a way that artificial light is not needed during the day.

- *Potential energy savings due to the adoption of new devices and energy-saving behavior*

Table 4.7 gives an overview of several energy savings options with the corresponding energy savings. These energy savings were gathered from literature, surveys, specifications of the appliance type, and experts. Further explanation is provided below the table.

Table 4.7: Potential energy savings of devices, passive building principles, and energy saving behavior

No	Savings options	Savings up to	Source
1	Replace incandescent lamps with LEDs	85%	Milieu centraal, 2018 Caperhart et al., 2008 Kreith & Goswani, 2008
2	Replace Fluorescent TL-lamps with LEDs	66%	Ledwereld, 2018
3	Replace conventional air-conditioners with inverter designs	40%	Specification of the appliance
4	Application of OWAC or SWAC	65%	Cooling experts
5	Efficient refrigerators	70%	Specification of the appliance
6	Energy-savings behavior	5%	Survey, section 4.1.3
7	Building energy-efficiency improvements	11%	Experts

The results of the surveys presented in Sections 3.7 and 3.8 demonstrated that almost all the hotels and supermarkets in Curaçao have energy-efficient lighting systems. This in contrast with the residential sector and office buildings discussed in Sections 3.5 and 3.6. Most of the lighting systems in the residential sector are incandescent lamps, while in office buildings most of the lighting systems are TL-fluorescents. Replacing traditional incandescent lamps with LED lamps will reduce the energy use by approximately 85%, while the replacement of traditional fluorescent TL-lamps with LED lamps yields a reduction of up to 66%.

Replacing a conventional non-inverter air conditioner with an energy-efficient inverter air conditioner can save up to 70% of energy use per air conditioner, depending on the type and brand of the air conditioner. In our

estimation, we take an average reduction of 40%. As discussed in Section 4.3.4, the OWAC and SWAC technologies can reduce the required air conditioner energy use by up to 65%. For hotels located near the sea, we therefor assume a 65% reduction in energy use for their cooling systems.

Energy-efficient refrigerators can save up to 70% of energy compared to inefficient refrigerators. For the residential, hotel, and commercial sectors, we assume a 50% reduction in refrigeration energy demand, and 20% for supermarkets. The lower estimation for supermarkets is due to the fact that most of the supermarkets already possess energy-efficient refrigerators.

- *Assumptions made to forecast potential energy savings*

The forecasting of energy savings is a complex task. As mentioned previously, energy savings are dependent on several factors. There is no forecasting information yet available about potential energy savings in Curaçao. To estimate the energy savings potential for Curaçao, a number of assumptions have to be made. These assumptions are based on the results of the conducted surveys, our experience in this area, and the developments that are taking place in Curaçao. It is assumed that by 2030, approximately 70% of the residents and offices will have replaced their energy-inefficient appliances by energy-efficient alternatives. The survey found that most of the standard, import, and export industries already use energy-efficient appliances. For the export industry, we will assume that about 50% of the hotels will replace their air conditioners with more energy-efficient cooling systems air conditioners such as OWAC or SWAC. Most of the industries already use energy-efficient lamps. We assume that the energy use of the lighting systems of the industries will drop by 20% due to techniques to improve lighting efficiency, for example, through lighting controls. It is also assumed that 50% of the supermarkets will further reduce the energy use of refrigerators. And with respect to street lighting, at this moment, a negligible number of streetlights in Curaçao make use of LED lamps. We assume that, by 2030, all street lighting systems will have been replaced by LED lamps, with an energy use reduction of about 50%.

Energy savings through the adoption of energy-efficient appliances are estimated at about 189 GWh in total, followed by passive building energy-

efficiency improvements of approximately 25 GWh, and energy-saving behavior of around 11 GWh. Most of the savings obtained through the adoption of energy-efficient appliances will be realized through the adoption of new lighting systems (44%), followed by air conditioners (35%), and refrigerators/freezers (21%). Furthermore, the expected savings through energy awareness behavior will mainly be realized in the residential sector (44%), followed by the industrial sector (32%) and the commercial sector (24%). In addition, this study found that in Curaçao, energy savings through building energy efficiency will primarily be obtained in the commercial sector (39%), followed by the industrial (32%) and the residential sectors (30%).

- *A forecast of potential energy savings in Curaçao in the period 2019-2030.*

Based on the assumptions made in the preceding paragraphs, a detailed estimation of the energy savings potential in Curaçao is provided in Appendices 7A, 7B and 7C. From the data in Appendices 7A, 7B and 7C it can be concluded that the total energy savings potential for Curaçao in 2030 is significant: total energy demand can be reduced by approximately 30%. As mentioned earlier in this section, a potential increase in the energy efficiency of small appliances was not taken into account in this estimation. This means that the energy savings potential is expected to be even higher than the forecasted 30% of total energy demand in 2030 (Appendices 7A, 7B and 7C).

The greatest energy savings in Curaçao will be realized in the residential sector (111 GWh, see Appendices 7A, 7B and 7C), mainly through the adoption of energy-efficient lighting systems, air conditioners, and refrigerators/freezers. Appendix 8 illustrates the timeline of the total energy demand for the period 2014 through to 2030.

4.5 Conclusions on energy savings options and energy saving potential for Curaçao

This chapter has addressed the third research question of this thesis: 'What are the energy savings options and what is their energy saving potential in Curaçao?' To provide an answer to this research question, an in-depth review was conducted of relevant scientific literature, reports, and

documents. This was complemented with a number of field studies. Several energy saving options have been identified and were described in detail in the preceding sections of this chapter as follows:

1. reduction of standby power losses;
2. adoption of passive building design principles;
3. adoption of techniques to improve energy efficiency of lighting systems;
4. adoption of energy-saving options for refrigerators, cooling systems, washing machines and office appliances; and
5. adoption of energy saving behavior by boosting consumer awareness.

The overarching conclusion that can be made on the basis of the preceding sections is that Curaçao has an overall energy savings potential of roughly 30% of the current energy demand.

CHAPTER 5

Towards 100% renewable energy production

In this chapter, the fourth research question will be answered: ‘How to realize a 100% renewable electricity production system for Curaçao?’. To answer this question, a literature review on the energy efficiency of electricity production and renewable energy sources was conducted and complemented with in-depth interviews with three experts and stakeholders from Aqualectra, Curaçao’s utility company (the Chief Technological Officer; the Head of the Asset Management Department; and an expert in electrical engineering).

The remainder of this chapter is organized as follows.

- Section 5.1 introduces the process steps that have been followed to enhance the sustainability of electrical power production in Curaçao.
- Section 5.2. elaborates on opportunities to enhance the sustainability of electrical power production in Curaçao.
- Section 5.3 presents a roadmap to make the electricity production of Curaçao free from fossil fuels.
- Section 5.4 presents the conclusions regarding the question of how electricity production can be made free of fossil fuels.

5.1 The process steps to enhance the sustainability level of the electrical power production in Curaçao

To date, utility companies are looking for ways to improve the energy efficiency of power plants and minimize their carbon footprint in order to make their power plants more sustainable (Closepet & Rao, 2015). As explained in the introduction, this section explains the process steps that can be followed to substantially enhance the sustainability of electrical power production in Curaçao. This process is based on information provided by

Aqualectra (2017) and literature by Lund (2007) and Volpi, Jannuzzi, and Gomes (2006).

The three process steps are to define:

1. the objectives of sustainability improvements to electricity production in Curaçao;
2. the diversification of electrical power production in Curaçao; and
3. how energy efficiency can be increased, and 100% renewable energy production can be realized.

1. Objective of the sustainability level improvement

As mentioned previously, electrical power production in Curaçao heavily depends on imported fossil fuels. The emphasis of the Curaçao government and the utility company Aqualectra is to reduce the use of non-renewable energy systems (non-RESs). The main reasons for this are to reduce environmental pollution and to become less dependent of imported fossil fuels.

As formally recorded (Aqualectra, 2017) the objectives of improving the sustainability of electricity production in Curaçao are:

1. to reduce environmental pollution and mitigate its negative effects;
2. to minimize the dependence of electricity production on imported fossil fuels;
3. to enhance supply reliability; and
4. to lower the cost of electrical power production.

To achieve these objectives, power production in Curaçao needs to move towards a more diversified and energy-efficient production of electrical power.

2. Diversification of electrical power production

Utility companies in general strive to have a diversified system of electrical power production, meaning that the electricity produced comes from various types of energy sources. The main aims of this production mix are to enhance the reliability of energy supply, to reduce reliance on a single fuel

type, and to improve environmental performance and affordability (Sadeghi & Larimian, 2018; CLP, 2014).

Currently, the energy supply mix in Curaçao consists of diesel generators, gas turbines, solar energy systems, and wind turbines. In addition, elsewhere, energy storage has increasingly become an essential component in the production mix as it can provide flexible backup for intermittent, renewable energy sources that do not always produce electricity. Energy storage can reduce the amount of non-RESs that are required to act as backup for the RESs (Critchlow & Denman, 2018). Thus, the increased implementation of more RESs and energy storage can reduce the environmental pollution and make an electricity production system less dependent on imported crude oil. Section 5.2 elaborates on the opportunities to implement more RESs in Curaçao.

3. Increasing the energy efficiency of electrical power production

Supply-side energy efficiency improvements is one of the main steps taken to increase the sustainability of electricity production (Lund, 2007). This chapter looks at five steps to enhance the efficiency of electrical power production. These steps are as follows:

- A. optimize the baseload (Peters & Burda, 2007);
- B. improve the efficiency of the generator sets (Volpi, Jannuzzi, & Gomes, 2006; Aqualectra, 2017);
- C. reduce energy losses in the transmission, distribution, and low-voltage infrastructure (Volpi, Jannuzzi, and Gomes, 2006; Aqualectra, 2017);
- D. apply tri-generation (Hernández-Santoyo & Sánchez-Cifuentes, 2003; Sugiarta, Tassou, Chaer, & Marriott, 2009; Harmsen, 2011); and
- E. implement the Organic Rankine Cycle (ORC), (Oyewunmi, Pantaleo, & Markides, 2017).

3A. Optimizing the baseload

The baseload of an electricity infrastructure is the minimum load that occurs over a lengthy period of time. The baseload is considered to be an important factor in the energy efficiency of the supply side because, generally, this is a

large constant load (“Technologies for sustainability systems”, 2018). Given both these facts, baseload generators should run at optimum efficiency and at a low cost. To achieve this, the most efficient power source in the power system will ideally run continually and cover some of this baseload, followed by the next most efficient power source and so on. Another approach is to consider efficiency, cost, and environmental improvement. While non-intermittent power sources generally cover the baseload, it is also possible to use intermittent RESs to meet some of the baseload (Peters & Burda, 2007). In Curaçao, the two wind turbine plants do provide baseload power, together with dispatchable non-RESs.

3B. Improve the efficiency of the generator sets

Improving the efficiency of electrical power production is a high priority for Aquallectra. In recent years, Aquallectra has taken several actions to improve the energy efficiency of its electrical power plants. The measure of how efficiently the power plants convert thermal energy into electricity is defined as the heat rate. The heat rate is the amount of thermal energy used by the power plants to produce one KWh of electricity and, contrary to efficiency, a low heat rate is better than a high heat rate. The formula to calculate heat rate is as follows:

$$\text{Heat rate} = \frac{\text{Energy input to the system}}{\text{Electricity production}} \left[\frac{\text{BTU}}{\text{kWh}} \right] \quad \text{Equation 5.1}$$

The heat rate of most of the diesel generator sets in Aquallectra’s power plants has been measured at between 10,000 and 12,000 BTU/kWh, while the heat rate of these generator sets given by the manufacturer is approximately 8,600 BTU/kWh. The heat rate of the gas turbine was also found to be high, and Aquallectra have taken various steps to lower the heat rate of its power plants, such as the following (Aquallectra, 2017):

1. heating the fuel to the temperature suggested by the manufacture of the generator sets to lower the viscosity of the fuel;
2. optimizing the operation of the turbochargers of the generators by cleaning them regularly using a turbo wash;
3. adjusting the pressure of the fuel pumps to the manufacturer’s indicated pressure;

4. applying time-based maintenance based on the maintenance schedule given by the manufacturer;
5. replacing the gas turbine's atomizing air compressor with a more efficient one and optimizing the inlet air process;
6. adjusting the regulation of the generator sets to increase the penetration of renewable sources; and
7. providing training to the operators to help them understand the theory behind regulating the spinning reserve, which is the extra energy that the generators can produce that is immediately available when energy demand increases.

The heat rate of the diesel generator sets has dropped considerably due to the above-mentioned actions. The heat rate of the diesel generator sets is now between 7,600 and 8,600 BTU/kWh. As a further result of these efficiency improvements, the heat rate of the gas turbine dropped significantly from 22,000 BTU/kWh to approximately 13,500 BTU/kWh. Aqualetra has reduced its total fuel use by approximately 30% by applying the aforementioned efficiency improvements (Aqualetra, 2017).

3C. Reduce energy losses in the transmission, distribution, and low-voltage infrastructure

Aqualetra has taken several steps to minimize the losses in the electricity transmission, distribution, and low-voltage infrastructure. For example:

1. introducing smart meters at the customer level. The introduction of these meters will reduce unaccounted energy use. This is the energy use that is not registered by the utility company. In Curaçao, the unaccounted energy use is approximately 15% of the total electricity demanded per year (Aqualetra, 2017).
2. replacing inefficient energy infrastructure components by energy-efficient components;
3. applying time-based maintenance on infrastructure components.
4. installing 220V (rather than 127 V) in the new villages. A higher voltage requires less current, and this will reduce energy losses in the cables and lines.

Energy losses in the infrastructure will be decreased by taking the previous mentioned actions to prevent losses in the transmission, distribution, and

low-voltage infrastructure. However, the exact savings cannot be calculated due to insufficient data.

Ad 3D. Tri-generation

Tri-generation is another technique to enhance energy efficiency on the supply side, and it is also referred to as combined heat, power, and cooling (CHPC). There is often confusion between tri-generation and co-generation. Another name for co-generation is combined heat and power (CHP). The difference between tri-generation and co-generation is that tri-generation includes an additional step than combined heat and power by also generating cooling from the waste heat. As such, tri-generation provides three forms of energy from a single type of fuel (Figure 5.2).

These three forms of energy are as follows (Harmsen, 2011):

1. cooling (chilled water);
2. heating; and
3. electricity production.

Figure 5.2: Three forms of energy generated by tri-generation (Harmsen, 2011)

Tri-generation is a proven technology that is extremely efficient and could be applied in the electricity power system of Curaçao to enhance efficiency. Tri-generation has several benefits, including the following (Hernández-

Santoyo & Sánchez-Cifuentes, 2003; Sugiarta, Tassou, Chaer, & Marriott, 2009; Harmsen, 2011; clean energy council, 2014):

1. it saves energy;
2. it offers a shorter payback time than conventional systems;
3. it produces three forms of energy – two of them by recycling heat;
4. it yields about 60% less carbon emissions than conventional systems; and
5. it is up to 80% more efficient than conventional systems.

Harmsen (2011) conducted research regarding the possible implementation of tri-generation with Power Plant I at Nieuwe Haven in Curaçao. The main objective of his research was to investigate if tri-generation was feasible for this power plant. Furthermore, his study had to demonstrate that tri-generation provides benefits, such as efficiency improvements, savings in energy costs, and a reduction in greenhouse gas emissions. His study focused on the generation of cooling by tri-generation due to the high energy demand for cooling in Curaçao. The results of his study have indicated that the implementation of tri-generation on the electricity Power Plant I at Nieuwe Haven is feasible and that it would provide several benefits. The power plant at Nieuwe Haven is surrounded by industries, a hospital, government agencies, shopping malls, and commercial properties. These have a large cooling demand and their proximity facilitates the transportation of produced cooling from this power plant to these sectors. In his study, Harmsen (2011) suggested that, apart from electricity and water, Aqualectra should also provide cooling to some customers. Through the implementation of tri-generation, Aqualectra will save on fuel use as well as on investments in new generator sets. This is because this system is 80% more efficient than the traditional electrical power plants, and customers supplied with cool water will use less electricity in meeting their cooling requirements. Furthermore, tri-generation also reduces overall carbon emissions. Harmsen further suggested implementing tri-generation on all of Aqualectra's non-renewable power plants.

3E. Organic Rankine Cycle

The ORC is an option that some electricity companies use to improve the efficiency of their power plants. The principle of the ORC is based on the use of hot exhaust gases produced by power plants to generate additional

electricity. The working fluid of this system is an organic, high-molecular mass fluid with a liquid-gas conversion temperature lower than the water-steam conversion temperature. The ORC works as follows: first, a turbo-generator acts as a conventional steam turbine and converts thermal energy into mechanical energy (Oyewunmi, Pantaleo, & Markides, 2017). This mechanical energy is transformed into electricity by a generator. The working fluid is converted from liquid to gas in the heat exchanger. The gas, after driving the turbine is carried to the condenser where it is converted back into a liquid, which subsequently moves in a closed loop to the heat exchanger (Figure 5.3). According to Baldasso, Andreasen, Meroni, & Haglind (2017), the fuel saved by applying the ORC is up to 8.9%.

Figure 5.3: ORC diagram (Greeninglease.com, 2018)

There are also energy saving opportunities in the offices, workplaces, and substations of the utility company. The energy saving opportunities that can

be applied in these areas have already been discussed in detail in Chapters 3 and 4.

5.2 Opportunities to enhance the sustainability of electrical power production in Curaçao

This section focuses on opportunities to increase the use of RESs in the electricity infrastructure of Curaçao. As explained previously, electricity production in Curaçao utilizes both intermittent RESs and non-RESs, and the system has no energy storage capability. For years, Aqualectra has been working to make its power plants more environmentally friendly. In 2014, Aqualectra commissioned a study to determine the maximum realistic amount of RESs in the electricity infrastructure. It is essential to determine the maximum allowable level of RESs in the electricity infrastructure while still guaranteeing power quality and reliability, and avoiding unacceptably high operational costs. A high penetration of intermittent and non-dispatchable RESs can lead to capacity balance complications and power regulation complications in a small isolated electricity infrastructure. These complications occur because the electricity production of intermittent RESs is not continuously available and cannot be controlled to match the fluctuating electricity demand. Moreover, a high penetration of intermittent and non-dispatchable RESs requires expensive backup capacity, which results in increased operational costs. One of the aims of the 2014 study was to determine to what extent solar energy and wind energy could be implemented in Curaçao without compromising the electricity supply. This study, commissioned by Aqualectra, concluded that the maximum solar and wind energy penetrations in the electricity grid of Curaçao were 55 MW and 45 MW respectively. To date there are 46.5MW of wind energy and approximately 14 MW of solar energy installed in Curaçao.

However, the 2014 study commissioned by Aqualectra did not consider energy storage possibilities due to the absence of economically acceptable grid energy-storage options. Further, the study covered only solar energy and wind energy because these two RESs had already demonstrated that they were technically and commercially viable in Curaçao. It would be possible to increase the penetration of RESs in the electricity infrastructure of Curaçao beyond the level indicated in the 2014 study if fast acting energy

storage could be applied. This is because fast acting energy storage units could smooth the intermittency of RESs, manage peak loads, regulate frequency and voltage, guarantee the reliability of renewable energy production, and create a more flexible distribution and transmission infrastructure (Critchlow & Denman, 2018).

Section 5.3. of this chapter includes a roadmap that has been designed to make electricity production in Curaçao free from fossil fuels. Before introducing this roadmap, subsections 5.2.1, and 5.2.2 will provide further details about the current energy sources used in Curaçao.

5.2.1 Non-renewable energy sources

Aqualectra's two newest electricity power plants are located at Dokweg. The power plant "Dokweg II A" was constructed and commissioned by Wärtsilä OY, a Finnish company. This power plant consists of four generators, each with a capacity of 8.9 MW. This project includes a 66 kV substation, which transforms the generated electricity from 11 kV to 66 kV and connects it to the Aqualectra network infrastructure. This power plant is located at "Industrieterrein Nieuwe Haven", one of the industrial areas of Curaçao. This power plant was inaugurated on 6th January 2015. This power plant is gas convertible, which means that it can be converted to work on gas fuel. This gives Aqualectra the option of switching from diesel fuel to gas in the future.

Another fossil power plant was inaugurated in April 2019. This power plant is located in the same industrial area, near the two other diesel power plants. The total capacity of this new electricity power plant is 38.8 MW, consisting of four generators of 9.7 MW. The electricity power will again be produced at 11 kV, and a transformer will transform the voltage to 66 kV. This power plant has dual fuel options and can work on both diesel and gas fuel. According to Aqualectra (2018), installing this new electricity power plant will avoid electricity production shortages for the coming 15 years.

Table 5.1 shows the remaining lifetime of the existing power plants in Curaçao. According to Table 5.1, within 15 years, approximately 67% of the total non-RESs will need to be replaced. Taking future energy security into

account, it would seem to be advisable to replace these non-RESs with RESs plus energy storage,. The use of biogas in place of conventional diesel fuel for electricity production is another option to make the electricity production more environmentally friendly.

Table 5.3: Remaining lifetime of the electricity power plants (Aqualectra, 2018)

No	Non-RESs power plants	Capacity [MW]	End of life
1	Dokweg I	37.8	2029
2	Dokweg I	10.6	2037
3	Dokweg II A	35.6	2041
4	Dokweg II B	38.8	2044
5	Isla	33.2	2032
6	Mundu Nobo	20.8	2032
	<i>Total non-RESs</i>	<i>176.8</i>	

5.2.2 Renewable energy sources

Wind turbines

As mentioned previously (2.4.2), the total installed wind capacity in Curaçao is 46.5 MW. This means that wind energy has already slightly exceeded the maximum allowable penetration (see 5.2). The main advantages of wind energy in Curaçao are the high performance achieved by the wind turbines and that these turbines are potentially able to produce energy throughout the entire year. However, a major disadvantage is that the output is intermittent and to an extent unpredictable.

Solar panels

The maximum allowable solar energy penetration in Curaçao was calculated at 55 MW, and the total capacity so far installed is about 14 MW. In the near future, approximately 41 MW of solar energy will be installed (Aqualectra,

2018). It is impossible to precisely determine the energy production of PV solar panels because the electricity production depends on various factors. These factors include the irradiance, the efficiency of the panels, shading, the orientation of the panels, the angle of inclination of the panels, the temperature of the panels, power losses due to soiling on the panels, and power losses in cables and other parts of the system such as transformers and inverters. In estimating the energy production of the solar panels in Curaçao, it is assumed that all the solar panels and their orientations are the same. Equations 5.2 to 5.6 are used in this study to calculate the energy production of the proposed total of 55 MW of solar panels (Dunlop, 2010). The total calculated energy production using these equations is about 76 GWh per year.

The equations, which were used to calculate the energy production of the 55 MW of solar panels are as following:

The minimum power output (P_g) of the solar panels, that is guaranteed by the manufacturer is:

$$P_g = P_{mp} * C_g * n_m \quad \text{Equation 5.2}$$

Where:

P_{mp} = the maximum DC power rating (at STC) of the solar panels in Curaçao.

C_g = the derating factor given by the manufacturer's power guarantee.

n_m = the number of modules.

The temperature-corrected power output, P_T is:

$$P_T = P_g + (P_g * C_{\%P} * [T_{amb} - 25]) \quad \text{Equation 5.3}$$

Where:

T_{amb} = the average expected module operating temperature

$C_{\%P}$ = the relative temperature coefficient for power

The net power output is:

$$P_{net} = P_T - (P_T * C_{loss}) \quad \text{Equation 5.4}$$

Where:

C_{loss} = a factor to account for power losses due to wiring and module mismatches

The inverter maximum AC power output is:

$$P_{inv-AC} = P_{net} * \eta_{inv} * \eta_{MPPT} \quad \text{Equation 5.5}$$

Where:

η_{inv} = the inverter power conversion efficiency

η_{MPPT} = the inverter MPPT efficiency

The average daily energy generation is then:

$$E = P_{inv-AC} * PSH \quad [\text{MWh/day}] \quad \text{Equation 5.6}$$

Where:

PSH = the average daily insolation for the location and array orientation, 5 hours for Curaçao.

5.3 Making electricity production in Curaçao free from fossil fuels

The desire to make the electricity production free of fossil fuels is stimulated by environmental concerns as well as economic and energy security issues.

This study will develop a plan to enable Curaçao to run on 100% renewable energy sources by 2033. The introduction of grid-scale energy storage in Curaçao will be one of the most significant steps in this process. Worldwide, grid-scale energy storage systems are used to improve electrical power systems that include intermittent RESs such as solar and wind energy (Amirante et al., 2017).

To date, electricity production in Curaçao has a large wind-power element (233.8 GWh/year), which contributes about 31% (2.4.2) to the total electricity production (Aqualectra, 2019). The contribution of solar energy (14.9 GWh/year) is about 2.8% (2.4.3) of the total electricity demand. The maximum allowed solar energy in the electrical infrastructure of Curaçao is about 76 GWh/year (see Chapter 4).

This current mix of the electricity production sources in Curaçao was primarily determined in such a way that it would ensure the stability of the electrical power system. Increasing the maximum allowed contributions of RESs will have a negative effect on the stability of the electrical power system in Curaçao if no other changes are made to the current electrical infrastructure. In this study, it is assumed that the stability of the electrical power system will be guaranteed if the RESs are fully backed up by grid-scale energy storage.

Between now and 2032, 91.8 MW of the existing 176.8 MW non-RESs will need to be replaced because the power plants will reach the end of their useful life (Table 5.1)

The main steps that can be taken to make electricity production in Curaçao free from fossil fuels are as follows:

- I. Replace the non-RESs that act as backup for the RESs by grid-scale energy storage.

The maximum estimated electricity production from RESs in the electrical infrastructure of Curaçao is approximately 309.8 GWh/year (wind energy 233.8 GWh/year and solar energy 76 GWh/year). As mentioned previously, in Curaçao, the non-RESs act as back up for the RESs. In the future, electricity

production can be reduced by 309.8 GWh/year, if grid-scale energy storage will be used as back-up for these RESs.

2. Reduce the total electricity production per year by the estimated energy savings.

In the coming years, the total electricity production in Curaçao can be reduced by an amount equal to the estimated energy savings achieved through various measures, equal to approximately 228 GWh (Chapter 4). Adding this to the amount saved by taking the back-up of the RESs into account, the total energy produced by the non-RESs can be reduced by 537.8 GWh/year. As a consequence, the Dokweg I and Isla power plants would not need to be replaced at the end of their lives. The maximum annual production from these two electrical power plants is about 643 GWh/year (Table 5.1), although in practice the annual production is less because they are not always in service.

3. Replace the electrical power plant at Mundu Nobo with solar energy.

The maximum annual power production from the electrical power plant at Mundu Nobo is approximately 164 GWh. Currently, the solar energy produced in Curaçao is about 14.9 GWh/year and the energy produced by the wind turbines is 233.8 GWh/year. The energy produced by the solar panels in Curaçao is very low compared with the wind turbines. For this reason, in this study, the electrical power plant at Mundu Nobo will be replaced with solar energy systems, so that the electricity production of these sources is roughly the same. This means that the installed solar energy in Curaçao has to be increased by 119 MW (to generate 164 GWh/year).

With this increase in solar, the total estimated energy produced by RESs will be approximately 412.7 GWh/year or 1.1 GWh/day (0.64 GWh/day wind and 0.49 GWh/day solar).

4. Use biogas instead of diesel in the Dokweg II A and Dokweg II B power plants. The electrical power plant at Dokweg II A could be modified to run on biogas and the electrical power plant at Dokweg II B has dual fuel engine generators and can work on both diesel and gas fuel. To achieve electricity

production free from fossil fuels in Curaçao, these two electrical power plants could be run on biogas instead of diesel.

Biogas

Biogas is a mixture of gases, which is produced from the decomposition of various types of organic waste under anaerobic conditions (a condition of absence of oxygen). Anaerobic digestion is another name for this process, because the decomposition occurs under anaerobic conditions. The main content of biogas is methane with a share between 50% and 75%, followed by carbon dioxide, which varies between 25% and 50%. Biogas has another small amount of gases (2-8%) such as oxygen, nitrogen, and traces of gases such as hydrogen, hydrogen sulphide, and ammonia (Abbasi, Tauseef, & Abbasi, 2012; Parkes, 2017; Varho, Winqvist, & Rikkonen, 2019; Wellinger, Murphy, & Baxter, 2013).

There is a wide variety of substrates, which can be anaerobically digested to produce biogas (Figure 5.4), such as (Wellinger et al., 2013):

1. agriculture crops and residues;
2. forestry crops and residues;
3. weeds;
4. industrial waste;
5. animal manure and waste;
6. municipal waste;
7. marine algae; and
8. sewage

Figure 5.4: Examples of substrates to produce biogas (Wellinger et al., 2013)

Biogas is being more and more used to produce electricity (Abbasi et al., 2012) and has an important position in various countries, especially in Germany, where attractive feed-in tariffs were applied in 2000 – 2016. In 2015, approximately, 50% of the worldwide biogas production occurred in

the European Union. The biogas in Germany represented approximately 50% of the biogas production in the European Union (Varho et al., 2019).

After a simple process of desulfurization and drying, biogas can be transformed into electricity (Wellinger et al., 2013). Biogas can also be upgraded to biomethane, after removing it from water, hydrogen sulphide, carbon dioxide, and other trace gases. Biomethane is flexible, easily storable and is chemically the same as natural gas. Thus, biomethane can be used for the same applications as natural gas, without the need to change any settings of the equipment (Parkes, 2017; Varho et al., 2019; Wellinger et al., 2013). Biomethane is considered as refined biogas, because it contains approximately 98% of methane (Parkes, 2017; Wellinger et al., 2013). Biomethane is also called renewable gas or green gas (Parkes, 2017; Wellinger et al., 2013). To avoid additional costs due to modification of the settings of the electrical power systems at Nieuwe haven II A and B, these systems can run on biomethane. The main advantage of biogas for the society is that the production of biogas enables nutrient recycling, offers technology for organic waste treatment, and minimizes GHG emissions, for example, methane from manure and organic waste (Varho et al., 2019).

5.3.1 Energy storage systems

Grid-scale energy storage

Electricity power demand is subject to fluctuations throughout the day due to the changing activities of customers. To guarantee power quality and reliability, the electricity power production must be able to match this fluctuating demand. In addition, the electricity power supplied by non-dispatchable RESs also fluctuates during the day due to the changing nature of wind and radiation. This makes it more difficult for utility companies with significant renewable contributions to match electricity power supply with demand.

Whereas the electricity power output of dispatchable fossil fuel plants can be regulated in line with electricity demand, the electricity power output of non-dispatchable RESs cannot be varied to meet the electricity power demand. Often, this can lead to electricity power outages and load shedding. Grid-scale energy storage can be very effective in ensuring a reliable flow of

electricity when a mix of dispatchable fossil fuel sources and non-dispatchable RESs are used.

Nowadays, grid-scale energy storage systems have become an important component in electricity grids. They are also seen as a basic requirement for a future sustainable and innovative energy production system (Amirante, Cassone, Distaso, & Tamburrano, 2017). Many utility companies consider affordable grid-scale energy storage as the missing link between reliability and non-dispatchable intermittent RESs (D'Aprile, Newman, & Pinner, 2016). Several countries such as Australia, Texas, Southern California, and Puerto Rico use them to regulate frequency and voltage, to smooth the irregularity of RESs, and to manage peak loads (Critchlow & Denman, 2018).

Curaçao's utility company has not yet implemented any grid-scale energy storage systems as part of its infrastructure. The main barrier that impedes the implementation of grid-scale energy storage in Curaçao is the high cost of energy storage. However, in the last few years, the costs of batteries have declined rapidly, due to the high demand for electric vehicles and consumer electronics (Frankel, Kane, & Tryggestad, 2018). From 2012 to 2017, the cost of batteries dropped by more than 50%. Trends indicate that battery costs will continue to decline in the coming years. In addition, the costs of battery-related hardware such as inverters, containers, and climate control equipment have also declined. These factors make using batteries in the electricity sector more attractive. Further, several utility companies have replaced conventional power generators by batteries (Frankel et al., 2018). It is important to note that energy storage can be placed on both the supply and demand sides. Some countries, including Japan and Germany, provide incentives to stimulate residential energy storage implementation. This is in order to minimize the intermittent effects caused by PV installations (Spector, 2018).

Currently, there are many energy storage systems available (Mahlia, Saktisahdan, Jannifar, Hasan, & Matseelar, 2014; Ter-Gazarian, 2011) such as:

1. thermal energy storage;
2. pumped hydro storage;
3. hydrogen and other synthetic fuels;
4. flywheel storage;

5. capacitor bank storage;
6. lithium batteries;
7. superconductivity energy storage;
8. compressed air energy storage; and
9. concrete low-cost blocks (Aouf, 2018; Hanley, 2018; Irving, 2018; Piconi et al., n.d.; Spector, 2018).

Amirante et al. (2017) indicated that pumped hydroelectric storage, flywheel storage, and lithium batteries can be considered as mature technologies that can be used for large grid-scale energy storage. Moreover, lithium batteries and flywheels are efficient, inexpensive, and durable.

Storing energy in tower of concrete blocks

The Swiss startup energy-vault has developed an innovative energy storage system that uses concrete blocks. This technology was inspired by the relatively mature pumped hydroelectric technology that depends on gravitational energy and the movement of water to produce electricity. The physics fundamentals in this innovative system are identical to those in pumped hydroelectric systems. The main difference is that, in this innovative system, concrete blocks are used instead of water (Hanley, 2018; Irving, 2018; Piconi, Pedretti, Kerr, Fyke, & Gross, n.d.; Spector, 2018).

To keep equipment costs low, energy-vault uses off-the-shelf components that for years have been manufactured by Siemens and ABB. To further lower the price of the system, as well as the negative environmental impact, the blocks are made from waste materials including concrete debris.

Other advantages of this grid-scale energy storage system are (Piconi et al., n.d.) that it is:

1. simple and safe to construct;
2. easy to construct the foundation pad;
3. self-constructing crane;
4. block material can be constructed on site; and
5. the cost per kWh of this system is 50% lower than that of current grid-scale energy storage.

In addition, this system has a lifetime of 30 to 40 years (Hanley, 2018; Irving, 2018; Spector, 2018), which is longer than that of batteries which is approximately 20 years (Hanley, 2018).

Although this system can be used to store energy for long periods, it can also be used to provide short and medium term ancillary services (services provided to support electricity transmission from the production site to the customer) to maintain a reliable electricity system due to its very fast response time (Piconi et al., n.d.). Furthermore, the concrete blocks could be made in Curaçao.

Given these advantages of the grid-scale energy storage system based on concrete blocks, this system is proposed in this study as grid-scale energy storage for Curaçao.

Construction

A tall crane consisting of six arms lifts the blocks off the ground creating a tower. Potential energy will be stored in this tall tower of concrete blocks. Later, the concrete blocks can be dropped back to the ground (Figure 5.5) converting the potential energy into kinetic energy which is then converted into electricity (Aouf, 2018; Hanley, 2018; Irving, 2018; Piconi et al., n.d.; Spector, 2018). Each system consists of 5,000 concrete blocks weighing approximately 78,000 kg in total (15.6 kg/block). The price of a 16 kg concrete block in Curaçao is about 2 USD. According to Shieber (2018), the price of one such system is between 7.4 million USD and 8.5 million USD, excluding transportation costs.

Figure 5.5: Concrete blocks energy storage (Irving, 2018)

Operating parameters

The operation of this system is full automated. Specially engineered control software is used to regulate the movement of the blocks and to avoid dangerous swaying.

The storage capacity of such a system is between 10 and 35 MWh (Piconi et al., n.d.). The standard configuration provides 35 MWh of energy storage with a maximum power delivery of 4 MW (Irving, 2018). Its overall efficiency is approximately 85% (Hanley, 2018; Piconi et al., n.d.). Further losses in the electrical cables and electrical components are up to 5%.

Grid-scale energy storage should be installed close to the RESs, for instance at Tera Kòrá and Playa Kanoa where the wind farms are located, to keep the losses in the electrical cables low.

The estimated electricity demand in 2033 is about 607 GWh/year, which is approximately 1,7 GWh/day. The estimated electricity demand = the estimated electricity without taking the estimated savings, 756 GWh/year

(Appendix 8) – the estimated savings, 226.8 GWh/year (30%) + energy supply for the water production, 33 GWh/year + the unaccounted energy use, 45 GWh/year.

The unaccounted energy use in Curaçao is about 12% of the total energy distribution (Aqualectra, 2018). We assume that by the introduction of the smart meters, the unaccounted energy use will drop with 6% in 2033 (approximately 45 GWh/year).

The power plants at Dokweg II A and II B, then running on biogas, can produce approximately 1.6 GWh/day. If the n-2 criteria is applied, meaning that the two largest generators (each 9.7 MW) will not be in service, these two power plants will produce about 1.2 GWh/day. This is because the two 9.7 MW generators can produce 0.4 GWh/day.

It is very unlikely that the total electricity production from the RESs in Curaçao is zero (Meteorological Department Curaçao, 2018). For this reason, we assume that the total electricity produced by the RESs per day will be at least 0.27 GWh/day (25% of the total production per day). In this case, the grid-scale energy storage must deliver $1.7 - 1.2 - 0.27$ GWh/day = 0.23 GWh/day. Taking into account the 85% efficiency of the grid-scale energy storage and the 5% losses in the electrical cables and components, the capacity of this energy storage system must be at least 0.31 GWh/day. This corresponds to nine grid-scale energy storage units, requiring in total 45.000 concrete blocks. The total cost of these energy storage systems is between 66 and 76 million USD.

Table 5.2 provides an overview of the capacities of the RESs, non-RESs, and the grid-scale energy storage units that will be applied in Curaçao to achieve an electricity production free from fossil fuels.

Table 5.2: Power plants and energy storage for electricity production free from fossil fuels

No	Power plants and grid-scale energy storages	Capacity [MW]
1	Dokweg II A/ Biogas	35.6
2	Dokweg II B/ Biogas	38.8
3	Solar energy plants	133.0
4	Wind energy plants	46.5
5	Energy storage/concrete blocks	36
	<i>Total</i>	<i>289.9</i>

Table 5.3 presents a preliminary timeline for the future mix of electricity production in Curaçao.

Table 5.3: Timeline for the implementation of RESs and grid-scale energy storage.

No	Proposed activities	2019-2029	2029	2030-2032	2032	2033
1	Implement 41 MW solar energy and corresponding energy storage	x				
2	Implement energy storages for the current RESs			x		
3	Phase-out Dokweg I power plant		x			
4	Phase-out Isla power plant				x	
5	Phase-out Mundu Nobo power plant				x	
6	Replace diesel by biogas in remaining power plants					x

5.4 Conclusions on improving supply-side sustainability

This chapter has provided an answer to the fourth research question of this thesis: “How to realize a 100% renewable electricity production system for Curaçao?” To answer this question, an in-depth literature study related to the energy efficiency of electricity production and renewable energy sources, and interviews with stakeholders were conducted. To gain insight into how to increase the sustainability of electricity supply on the island of Curaçao, a process was developed in this study.

The results of this study has shown that supply-side energy efficiency improvements can be achieved in several ways, including:

1. optimizing the baseload;
2. improving the efficiency of the generators;
3. reducing energy losses in the transmission, distribution, and low-voltage infrastructure; and
4. using the heat produced by the thermal power plants.

Further, the electricity production in Curaçao can be made free from fossil fuels by implementing the following actions:

1. replacing the conventional backups for the RESs by grid-scale energy storage based on concrete blocks;
2. reducing non-RES electricity production by an amount equivalent to the estimated energy savings;
3. using more wind and solar energy; and
4. use biogas instead of diesel in the remaining thermal plants.

CHAPTER 6

Discussion, conclusions, and recommendations

The main goal of this study has been to *structurally improve energy efficiency in Curaçao and to develop a roadmap to realize a 100% renewable energy production system*. To achieve this goal, this thesis has provided answers to the following research questions:

1. What is the current state of Curaçao's electricity infrastructure?
2. What is the status of energy use and energy behavior in the household, the commercial, and the industrial sectors in Curaçao?
3. What are the energy saving options and energy savings potential in the household, the commercial, and the industrial sectors in Curaçao?
4. How to realize a 100% renewable electricity production system for Curaçao?

In this final chapter, the findings and results for each research question are summarized and discussed in Section 6.1. Sections 6.2 and 6.3 describe the scientific and societal contributions of this study respectively. The limitations of this PhD study and suggestions for future research are addressed in Section 6.4.

6.1 Summary of results and general discussion

This research was guided by three themes. First, this research examined the energy situation and use on both the demand side and the supply side in Curaçao. Second, this research investigated several options to improve energy efficiency on the demand and the supply sides. Third, this study investigated the possibilities to replace non-RESs by renewable energy sources to make electricity production in Curaçao completely free from fossil fuels. This section combines and discusses the most important findings of this PhD research.

6.1.1 The current state of Curaçao's electricity infrastructure

The current total installed power capacity in Curaçao is 237.3 MW and consists of three diesel power plants, one gas turbine, two large and some smaller wind farms, and a limited number of PV solar systems. The study showed that Curaçao has a relatively high proportion of intermittent RESs

in the mix: about 34% of the current electricity demand is met by intermittent RESs.

As in all countries, the electricity demand in Curaçao is governed by the activities of the users and varies accordingly during the day. Further, current electricity production appears to be very variable. The relatively high fluctuation in electricity production by wind turbines is caused by the variable wind speed, and the necessary servicing and maintenance of the wind turbines. Further, changes in irradiance induce rapid variations in PV electricity production during the year. Currently, the non-RESs provide backup for these fluctuating RESs. So far, the electricity infrastructure does not make use of grid-scale energy storage systems. An important step that has to be taken to reduce and/or to make the electricity production in Curaçao free from fossil fuels is the introduction of grid-scale energy storage in the electricity infrastructure to balance out the variations in RES outputs.

6.1.2 The current energy use and energy behavior in Curaçao

An important step in this research has been to classify the energy use and the characteristics of energy behavior in Curaçao. Two surveys and two field studies were conducted to this end:

- a survey study in which 384 households in Curaçao participated;
- a survey study in which 333 representatives of office buildings participated;
- a field study to examine the energy use and energy efficiency of 22 hotels; and
- a field study to examine energy use and energy efficiency in 9 supermarkets.

Households

This study revealed that:

- air conditioners (23%), lighting (28%), and refrigerators (22%) are the appliances that use the most electrical energy in households;
- there are differences between income categories in the use of energy efficient appliances. About 42% of high-income households have at least

one energy-efficient appliance, while only 25% of middle-income households and 15% of low-income households have such appliances;

- cost saving, and not environmental concerns, appears to be the most important driver in stimulating energy saving behavior; and
- most households in Curaçao are unaware of all the energy-efficient options available that they could apply to reduce their costs. The majority of households in Curaçao are only using basic techniques to save energy such as switching off lamps when they are not in use.

Office buildings

This study found that:

- there is a high level (89% of those surveyed) of energy saving awareness. The greatest energy awareness (91%) was in businesses with less than five employees;
- cost saving, rather than environmental concerns, appears to be main driver for energy saving behavior; and
- Air conditioners (54%), indoor lighting (23%), and computers (21.5%) are the main contributors to the overall energy load in office buildings.

Hotels

This study revealed that:

- cooling (41%), refrigerators (20%), water heating (15%), and lighting (15%) are the main energy consumers in hotels in Curaçao;
- besides the widespread use of energy-efficient lighting and air conditioners, 50% of the hotels use energy efficient LED televisions;
- notwithstanding the high energy awareness in this sector, only 59% of the hotels have energy-efficient air conditioners. This leaves considerable room for energy efficiency improvements; and
- so far, only one hotel makes use of PV systems to generate part of its own electricity. Also occupancy sensors are only used by a very limited number of hotels.

Supermarkets

This study revealed that:

- refrigeration units appear to be highest energy user (32%), followed by air conditioners (27%), and lighting (21%);
- all the supermarkets in the conducted field study make use of closed refrigeration and in-store freezers, which are more efficient than open refrigerators and freezers.

With a combined energy use of at least 73% of the total energy used, the conclusion is justified that air conditioners, lighting, and refrigerators are the main energy demands in households, hotels, and supermarkets. For office buildings, the energy share of air conditioners and lighting is even higher at 77%. Fortunately, these types of appliances have large energy saving potential.

6.1.3 Energy saving options and energy saving potential in Curaçao

Another important step in this research has been to identify energy saving options and the energy saving potential in Curaçao. The most significant conclusion that can be made on the basis of the findings described in Chapter 4 is that Curaçao has an overall energy savings potential of approximately 30% of the current energy demand.

With respect to energy saving options, Chapter 4 provides a rich variety of options to substantially reduce energy consumption:

- Reduction of domestic standby power losses;
The study shows that Curaçao's total standby power consumption is, on average, approximately 5% of its total annual residential electricity consumption. Options to reduce standby power losses besides technical options include the introduction of import regulations and public awareness through awareness-raising programs on TV and other media.
- Adoption of passive building design principles;
Based on an extensive literature review on passive building designs for tropical areas, and a field study that included 626 buildings in Curaçao, the following design principles are proposed.

1. orientate buildings in a direction that takes advantage of the prevailing northeast Passat wind on the island;
2. facilitate natural ventilation as much as possible through openings (windows, ventilation gaps, and doors), and stack and solar chimneys;
3. increase the wind speed through buildings by creating squeeze points;
4. employ low-thermal mass materials to reduce heat gain;
5. use light colors for the external walls and roofs;
6. shade the building to keep the sun off the building;
7. install insulation in the walls and above the ceiling; and
8. create roof spaces with proper natural ventilation. These will act as buffer zones and reduce heat gain and heat transfer through the building.

A building energy codes program promoted by the government and adopted by the population could potentially reduce local energy consumption by 11%.

- Adoption of measures to improve energy saving
 1. the replacement of incandescent lamps by LED lamps will save 85% of existing consumption, and replacing TL-lamps by LED lamps will reduce usage by 66%;
 2. the replacement of conventional air-conditioners by inverter-based alternatives will save 40% in energy costs;
 3. replacing old refrigerators with energy efficient ones will reduce energy use by up to 70%; and
 4. adoption of OWAC or SWAC systems for cooling buildings situated near the sea will result in a 65% saving in their air conditioning energy use.
- Increasing consumer awareness of energy saving behavior

The introduction of energy awareness programs by the Government of Curaçao to stimulate energy saving behavior could potentially reduce energy use on the island by up to 5%.

- Supply-side energy saving potential

This study has shown that energy efficiency on the supply side can be improved by:

1. optimizing the baseload since the most efficient electricity sources should provide baseload power;
2. improving the efficiency of the generators to reduce fuel use by approximately 30% in Curaçao;
3. reducing energy losses in the transmission, distribution, and low-voltage infrastructure; and
4. using the waste heat produced by the non-RESs, which will increase efficiency by about 9%.

6.1.4 Towards a 100% renewable electricity production system in Curaçao

A final significant research output of this study is the development of a roadmap towards a fossil-fuel-free energy production system in Curaçao. Chapter 5 provides the details of the steps that need to be taken to realize this 100% sustainable electricity production system:

1. Replace the conventional back-up of RESs with grid-scale energy storage units;
2. Reduce electricity production to match the estimated energy savings;
3. Increase the installed capacity of solar-based energy systems to replace decommissioned oil-fueled power plants;
4. Use biogas in place of diesel fuel in the remaining thermal generator sets.

A grid-scale energy storage system based on concrete blocks is proposed in this research for Curaçao. This system has several claimed advantages such as:

1. long lifetime;
2. simple and safe to construct;

3. low environmental impact;
4. concrete blocks can be constructed on site;
5. easy to construct foundation pad;
6. self-constructing crane; and
7. low cost

Taking into account the different sources and fuels used for the electricity production in Curaçao, the CO₂ emission can be calculated as follows: emission factor * amount of electricity production (Reich, Alsema, van Sark, & Nieuwlaar, 2007; Thomson, Harrison, & Chick, 2017; *Uk Government GHG Conversion Factor for company reporting*, 2018). By implementing the propositions in this thesis, the CO₂ emissions will be reduced from 143.373 kgCO₂/GWh per year in 2019 toward 11.746 kgCO₂/GWh per year in 2033. This means a reduction of CO₂ emissions of about 92%. See table 6.1. for further details.

Table 6.1: CO₂ emissions for electricity production in Curaçao

No	Source	Curaçao in 2019			Curaçao in 2033		
		Production GWh/year	kgCO ₂ eq/kWh	kgCO ₂ /GWh/year	Production GWh/year	kgCO ₂ eq/kWh	kgCO ₂ /GWh/year
1	Wind	233,8	0,0113	2,642	233,8	0,0113	2,642
2	Solar	14,9	0,03	0,447	164	0,03	4,920
3	Non-RESs diesel	552,3	0,254	140,284	0	0	0
4	Biogas	0	0	0	209,2	0,02	4,184
Total		801		143,373	607		11,746

Figure 6.1 illustrates a flow diagram of the 100% renewable energy system in Curaçao in 2033. This flow diagram also includes the CO₂ emissions of both years 2019 and 2033.

Figure 6.1: Flow diagram of the 100% renewable energy system in Curaçao in 2033

6.2. Scientific contributions

This PhD thesis, of which the main research findings have been presented in the preceding section, makes three main scientific contributions related to the field of renewable energy and energy efficiency.

The first scientific contribution is the development of an approach to identify the current energy use in Curaçao and to analyze potential energy savings for Curaçao. This identification and analysis has been conducted for the supply-side electricity production as well as demand-side energy use. Curaçao has been taken as a case study but the approach is generic in the

sense that it can also be applied to identify the energy use and energy saving potential of other Small Island Development States (SIDS).

The second scientific contribution of this research is the development of a wide array of options through which Curaçao can not only drastically reduce its energy use on the demand-side but also on the supply side in electricity production.

The third scientific contribution of this research specifically concerns the electricity supply side and is the development of an approach by which Curaçao and similar SIDS can realize a 100% sustainable energy production that is based on wind, solar, and biogas as the only energy sources.

6.3. Societal relevance

Curaçao, as part of the Kingdom of the Netherlands, has signed up to the objectives of the Paris Agreement (2015). The findings in this PhD thesis provide clear directions for SIDS in general and for Curaçao more specifically to meet the objectives of the Paris Agreement.

Implementation of the proposed roadmap included in this PhD thesis will change Curaçao into an island that has a fully sustainable energy production system by 2033. In addition, implementation of the proposed roadmap will reduce CO₂ emissions by approximately 92 percent. Finally, the thesis has also identified multiple ways to structurally reduce energy consumption. Implementation of the various proposed options will lead to substantial cost savings which can have a positive impact especially for lower income groups.

6.4 Limitations

In this section, some important limitations are addressed. The first limitation of this study is in regard to the various surveys conducted to determine the energy-use pattern and energy behavior in Curaçao. These surveys focused on the residential sector, office buildings, hotels, and supermarkets. The industrial sector in Curaçao also includes other types of businesses that were not addressed. Notwithstanding this limitation, it is argued that the insights obtained are sufficient to determine the energy-use pattern as well as to estimate the energy savings potential in Curaçao.

A second limitation is in relation to achieving energy savings through behavioral changes and energy management systems. This study paid insufficient attention to these factors. There is considerable literature that indicates that both topics play an important role in realizing energy efficiency improvements in both residential and non-residential sectors.

A third limitation of this study relates to the ideas for electricity production in Curaçao free from fossil fuels. The processes to determine the penetration of RESs and non-RESs, and the application of appropriate energy storage technologies, in a small isolated electricity infrastructure is very complex. Many constraints related to implementing RESs, non-RESs, and energy storage are based on technical factors. This requires, besides several feasibility studies, a comprehensive analysis including transient stability analysis and frequency stability analysis. This study does not go into sufficient detail to cover transient stability and frequency stability issues with the proposed electricity infrastructure. Nevertheless, this study has convincingly shown that it is possible to meet electricity demands in Curaçao without using fossil fuels.

6.5 Recommendations

The study conducted in this thesis has raised various questions that need further research. This last section therefore presents an overview of several recommendations for future study as well as policy recommendations in order to improve energy efficiency in Curaçao.

Recommendations for a coherent energy policy program

Chapters 3 and 4 have shown that energy use is closely related to the lifestyle and income of residents and the types of businesses they engage in. It was clear that there are many opportunities to improve energy efficiency in Curaçao, in both the residential and business sectors. An important explanation of this fact is that there are already a variety of technological solutions available that can provide considerable energy savings in both sectors. However, to successfully improve energy efficiency, some barriers

need to be overcome. The major barriers that impede further improvements in energy efficiency in Curaçao are:

- a limited energy policy framework;
- a lack of awareness among consumers;
- the relatively high price of energy-efficient appliances;
- a lack of funding;
- a lack of incentive support; and
- inadequate data and information.

To overcome the identified barriers, an active role of the government will be essential. To this end, the development of an appropriate energy-efficiency policy program for Curaçao is required.

Important components of the proposed energy-efficiency improvement program are:

1. Financial incentives

The program needs to offer monetary benefits for both the construction of energy-efficient buildings and the purchase of energy-efficient products and appliances to boost energy efficiency. Three such programs corresponding to the financial incentives program are hereby proposed:

- A tax incentives program: this program will offer tax reductions for all energy-efficient products purchased by residents and businesses (Geller, Harrington, Rosenfeld, Tanishima, & Unander, 2006; California Energy Commission, 2017; Altman et al., 2010);
- An energy-efficiency grant program (Geller et al., 2006): this grant program would benefit eligible Curaçao residents such as low-income households. For example, this program could help low-income households to purchase energy-efficient appliances as well as to renovate their dwellings according to energy-efficiency standards. The government of Curaçao, the utility company, or other organizations could finance this program; and
- A financial incentives program for energy-efficiency upgrades: this program would provide grants and/or tax incentives for energy-

efficient upgrades in the residential, commercial, and industrial sectors (Geller et al., 2006; Altman et al., 2010).

2. *Standby power program*

This program should include the setting of minimum standards for standby power loads, introducing regulations to encourage purchase and import of only 50 Hz and/or 50/60 Hz appliances, and an information campaign. The introduction of minimum standards for standby power ratings should be accompanied by a policy to discourage the import of appliances not adhering to the minimum standby standards. Furthermore, the main objectives of the information campaign should be to increase awareness of standby losses and stimulate the purchase and import of appliances with low standby power loads (Geller et al., 2006; 'California Energy Commission', 2017).

3. *Awareness and education program*

This program should encourage households and businesses to raise energy-efficiency awareness, stimulate the efficient use of energy, and encourage the purchase of energy-efficient appliances (Geller et al., 2006; 'California Energy Commission', 2017; Altman et al., 2010). In many countries, the government, the utility companies, educational institutions, and/or other institutions are responsible for such programs.

4. *Behavior-focused comparative energy use program*

The goal of this program is to motivate participants to reduce energy use through self-installation of inexpensive energy saving measures and free energy conservation actions ('California Energy Commission', 2017).

5. *Energy-efficient building codes program*

The purpose of this program is to improve energy-efficiency by enhancing the design and construction of buildings by using energy-efficient building codes. These codes should be applied to the planning,

design, operation, construction, use, and occupancy of every renovated building or new building ('California green building standards code', 2010; Geller et al., 2006).

6. *Phase-out low-efficiency lamps program*

The main objective of this program would be to phase-out low-efficiency lamps (as in 'La Revolución Energética: Cuba's Energy Revolution, 2009). This program would include banning the import and sale of low-efficiency lamps. Besides this, the government would need to provide subsidies to low-income households for the purchase of relatively expensive energy-efficient lamps.

7. *Research and development program*

A research and development program would oversee research to enhance energy efficiency by identifying energy-efficiency opportunities and by stimulating the development and commercialization of new energy-efficient technologies and practices (Geller et al, 2006). Furthermore, this program could identify market failures in Curaçao that hinder the implementation of energy-efficient technologies and practices.

Recommendations for sustainability assessment

The sustainability of an electricity power system depends on the mix of energy sources, including in the provision of energy back-up. There are no well-established models to assess the sustainability of an entire electricity power generation system. A way to assess the sustainability of the entire electricity power network, including all the energy sources and energy storage units attached to the power plants, is needed. This will help policymakers and utility companies to improve the sustainability of electricity production.

Recommendation for research into zero net-energy buildings

This study has not considered technologies for zero net-energy buildings. However, zero net-energy buildings can play a crucial role in demand-side energy efficiency and sustainability. Many countries have adapted their policies to minimize energy use by encouraging zero-energy buildings. Further research is needed on the relevance of zero-energy buildings to Curaçao, and the impact they would have on the utility company.

Recommendation for assessing sound energy as a way to cool buildings

The Dutch start-up SoundEnergy BV from Enschede has built a sustainable cooling machine that converts waste heat into cold. This device has a thermo-acoustic energy converter system that use sound waves to cool buildings. This system uses industrial waste heat or solar heat. This system does not consume other sources of energy and is maintenance-free ('Turn waste heat into profit': Koetsier, 2019). This study did not focus on this type of cooling device. Research is needed to examine the potential of thermal-acoustic systems and their potential for Curaçao.

Recommendation to consider other types of RES

This research has focused on only two types of RES: solar and wind energy. However, there are other RESs that could be applied in Curaçao including ocean thermal energy conversion (OTEC), waste to energy, tidal energy, geothermal energy, and hydrogen. Conducting economic and technical feasibility studies to evaluate and analyze the potential of these RESs in Curaçao is recommended.

Recommendation for modelling the proposed fossil-fuel-free electricity system

The process to accurately calculate the desired capacities of non-RESs, RESs, and grid-scale energy storage for the overall electricity production is complex. This process requires comprehensive analyses including transient stability analysis and frequency stability analysis. The transient analysis of an

electricity power system is a significant component when designing an electricity power system. The entire electricity infrastructure, including its components, must be modelled in a transient analysis. To investigate the impacts of the integration of RESs and energy storage into the electricity infrastructure will require all these sources and the energy storage system to be modelled in an analysis. Much of the information needed for this modelling will have to be gathered from various manufacturers. For these reasons, further study is needed to accurately calculate the appropriate capacities of the various renewable sources and the energy storage for the proposed electricity production system.

References

- Abbasi, T., Tauseef, S. M., & Abbasi, S. A. (2012). *Biogas energy*. New York: Springer. <https://doi.org/10.1007/978-1-4614-1040-9>
- Abrahamse, W. (2007). *Energy conservation through behavioral change : Examining the effectiveness of a tailor-made approach*.
- Adaptation tariffs renewable electricity generation. (2015). Willemstad, Curacao.
- Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., & Baharum, M. R. (2015). A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings*, 101, 153–162. <https://doi.org/10.1016/j.enbuild.2015.04.033>
- Alan, K., Meier, A., & Lebot, B. (1999). One Watt Initiative : a Global Effort to Reduce Leaking Electricity. *Energy*.
- Aldossary, N. A., Rezgui, Y., & Kwan, A. (2015). An investigation into factors influencing domestic energy consumption in an energy subsidized developing economy. *Habitat International*, 47, 41–51. <https://doi.org/10.1016/j.habitatint.2015.01.002>
- Ali, Y., Mustafa, M., Al-Mashaqbah, S., Mashal, K., & Mohsen, M. (2008). Potential of energy savings in the hotel sector in Jordan. *Energy Conversion and Management*, 49(11), 3391–3397. <https://doi.org/10.1016/j.enconman.2007.09.036>
- Altman, M., Michalski, J., Brenninkmeijer, A., Lanoix, J., Tisserend, P., Egenhofer, C., Ellison, D. (2010). *EU Energy Efficiency Policy-Achievements and outlook*. Brussels.
- Amirante, R., Cassone, E., Distaso, E., & Tamburrano, P. (2017). *Overview on recent developments in energy storage: Mechanical, electrochemical and hydrogen technologies*. *Energy Conversion and Management* (Vol. 132). Elsevier Ltd. <https://doi.org/10.1016/j.enconman.2016.11.046>
- Aouf, R. S. (2018). Energy-storing concrete bricks could be key to

proliferation of renewables. Retrieved 3 March 2019, from <https://www.dezeen.com/2018/12/17/energy-vault-energy-storing-concrete-bricks-technology/>

Aqualectra. (2015). Retrieved 11 June 2015, from www.aqualectra.com

Arteconi, A., & Polonra, F. (2017). Demand side management in refrigeration applications. *International Journal of Heat and Technology*, 35(Special Issue I), S58–S63. <https://doi.org/10.18280/ijht.35Sp0108>

Baldasso, E., Andreasen, J. G., Meroni, A., & Haglind, F. (2017). Performance analysis of different organic Rankine cycle configurations on board liquefied natural gas-fuelled vessels. Banfi, S., Farsi, M., Filippini, M., & Jakob, M. (2008). Willingness to pay for energy-saving measures in residential buildings. *Energy Economics*, 30(2), 503–516. <https://doi.org/10.1016/j.eneco.2006.06.001>

Banfi, S., Farsi, M., Filippini, M., & Jakob, M. (2008). Willingness to pay for energy-saving measures in residential buildings. *Energy Economics*, 30(2), 503–516. <https://doi.org/10.1016/j.eneco.2006.06.001>

Bastide, A., Lauret, P., Garde, F., & Boyer, H. (2006). Building energy efficiency and thermal comfort in tropical climates. Presentation of a numerical approach for predicting the percentage of well-ventilated living spaces in buildings using natural ventilation. *Energy and Buildings*, 38(9), 1093–1103. <https://doi.org/10.1016/j.enbuild.2005.12.005>

Böhringer, C., & Jochem, P. E. P. (2007). Measuring the immeasurable — A survey of sustainability indices, 63(1991), 1–8. <https://doi.org/10.1016/j.ecolecon.2007.03.008>

Boyle, G. (Ed.). (2009). *Renewable electricity and the grid. The challenge of variability*. (Second). Cross street London: Earthscan.

Brown, L., Eman, R., Halman, J., & Lauffer, E. (1974). *Bouw fysisch verantwoord bouwen op Curaçao*. Delft, The Netherlands.

BT&P. (2015). Retrieved 11 June 2015, from www.btnp.org

- Cairns Regional Council. (2011). Sustainable Tropical Building Design: Guidelines for Commercial Buildings. *Wetlands*, 48.
- California Energy Commission. (2017). *Highlights of the California Energy commission's 2017 accomplishments*. California.
- California Green building standards code. (2011). California.
- Caperhart, B. L., Turner, W. C., & Kennedy, W. J. (2008). *Guide to energy management* (Sixth). Georgia: The Fairmont Press, Inc.
- Carlsson-Kanyama, A., Lindén, A. L., & Eriksson, B. (2005). Residential energy behaviour: Does generation matter? *International Journal of Consumer Studies*, 29(3), 239–253. <https://doi.org/10.1111/j.1470-6431.2005.00409.x>
- Central Bureau of Statistics Curaçao. (n.d.). Retrieved 8 December 2015, from www.cbs.cw
- Chata. (2018). Retrieved from Chata.org
- Choi, H. S., & Huh, D. Y. (2005). Techniques to minimize power consumption of SMPS in standby mode. *PESC Record - IEEE Annual Power Electronics Specialists Conference, 2005*, 2817–2822. <https://doi.org/10.1109/PESC.2005.1582032>
- Clark, J. (2015). *Energy-Efficient Supermarket Heating, Ventilation, and Air Conditioning in Humid Climates in the United States*. Oak Ridge.
- Clement, K., Pardon, I., Driesen, J., Leuven, K. U., & Electa, E. (2007). Standby Power Consumption in Belgium. *Electrical Power Quality and Utilisation*, 1–4. <https://doi.org/10.1109/EPQU.2007.4424225>
- Closepet, A. S., & Rao, K. U. (2015). Supply Side Management for Cost Optimization in Developing Countries Suffering with Power Outage, (April), 319–325.
- CLP. (2014). Future fuel mix for electricity generation. Hon Kong.
- Critchlow, Julian & Denman, Aaron. (2018). *The Energy Revolution Of*

2018: Electricity Storage. Retrieved from
<https://www.forbes.com/sites/baininsights/2018/02/01/the-energy-revolution-of-2018-electricity-storage/#275065d06208>

D'Aprile, P., Newman, J., & Pinner, D. (2016). Energy storage can make money right now. Finding the opportunities requires digging into real-world data. Retrieved 4 April 2017, from
<https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/the-new-economics-of-energy-storage>

De Martino Jannuzzi, G., & Schipper, L. (1991). The structure of electricity demand in the Brazilian household sector. *Energy Policy*, 19(9), 879–891. [https://doi.org/10.1016/0301-4215\(91\)90013-E](https://doi.org/10.1016/0301-4215(91)90013-E)

Dennehy, E., & Howley, M. (2013). Energy in the Residential Sector 2013. *Sustainable Energy Authority of Ireland The*, 104. Retrieved from
http://www.seai.ie/Publications/Statistics_Publications/Energy-in-the-Residential-Sector/

Diaz, C. H. (2016). Advice from an architect: 10 tips to create a cooler home. Retrieved 11 December 2018, from
<https://www.rappler.com/life-and-style/arts-and-culture/122067-advice-architect-tips-cooler-home>

Division for Sustainable Development. (2013). Retrieved 11 September 2015, from
https://sustainabledevelopment.un.org/content/dsd/dsd_aofw_sids/sids_sidsnet.shtml

Duic, N., Alves, L. M., Chen, F., & Da Graça Carvalho, M. (2003). Potential of Kyoto protocol clean development mechanism in transfer of clean energy technologies to small island developing states: Case study of Cape Verde. *Renewable and Sustainable Energy Reviews*, 7(1), 83–98. [https://doi.org/10.1016/S1364-0321\(02\)00062-X](https://doi.org/10.1016/S1364-0321(02)00062-X)

Duić, N., & Da Graça Carvalho, M. (2004). Increasing renewable energy sources in island energy supply: Case study Porto Santo. *Renewable and Sustainable Energy Reviews*, 8(4), 383–399. <https://doi.org/10.1016/j.rser.2003.11.004>

- Dunlop, J. P. (2010). *Photovoltaic systems*. (J. F. Gosse, T. W. Stafford, & NJATC Staff, Eds.) (Second). Illinois: American Technical Publishers, inc. In partnership with NJATC.
- EEA Technical report (2013) Achieving energy efficiency through behaviour change: what does it take?, European Efficiency Agency, Technical report 5-2013, Copenhagen, 53pp.
- Ek, K., & Söderholm Patrik, P. (2010). The devil is in the details: Household electricity saving behavior and the role of information. *Energy Policy*, 38(3), 1578–1587. <https://doi.org/10.1016/j.enpol.2009.11.041>
- Energy Efficiency Guidelines for Office Buildings in Tropical Climate. (2013), (February 2013), 27. Retrieved from http://ecpamericas.org/data/files/Events/Saint Lucia Presentations/DGB.5-ExecutiveSummary_updated.pdf
- Entrop, dr. ir. A. G. (2013). *Assessing energy techniques and measures in residential buildings: a multidisciplinary perspective*. <https://doi.org/10.3990/1.9789036535366>
- Eurima. (2018). Trias Energica. Retrieved 12 December 2018, from <https://www.eurima.org/energy-efficiency-in-buildings/trias-energetica>
- European Environment Agency. (2013). *Achieving energy efficiency through behaviour change: what does it take? Luxembourg: Publications Office of the European Union, 2013*. <https://doi.org/10.2800/49941>
- Farhangi, H. (2010). The path of the smart grid. *IEEE Power and Energy Magazine*, 8(1), 18–28. <https://doi.org/10.1109/MPE.2009.934876>
- Frankel, D., Kane, S., & Tryggstad, C. (2018). The new rules of competition in energy storage.
- Fujii, Y., Yoshiura, N., Takita, A., & Ohta, N. (2013). Smart street light system with energy saving function based on the sensor network. *Proceedings of the Fourth International Conference on Future Energy Systems - e-Energy '13*, (January), 271. <https://doi.org/10.1145/2487166.2487202>

- Fung, A. S., Aulenback, A., Ferguson, A., & Ugursal, V. I. (2003). Standby power requirements of household appliances in Canada. *Energy and Buildings*, 35(2), 217–228. [https://doi.org/10.1016/S0378-7788\(02\)00086-5](https://doi.org/10.1016/S0378-7788(02)00086-5)
- Garcia, J. M., & Coelho, L. M. R. (2010). Energy efficiency strategies in refrigeration systems of large supermarkets. *Journal Of Energy*, 4(3), 63–70.
- Geller, H., Harrington, P., Rosenfeld, A. H., Tanishima, S., & Unander, F. (2006). Policies for increasing energy efficiency: Thirty years of experience in OECD countries. *Energy Policy*, 34(5), 556–573. <https://doi.org/10.1016/j.enpol.2005.11.010>
- Glover, D., & Sarma, M. (2002). *Power system analysis and design*. (B. Stenquist, Ed.) (Third). Pacific Grove: Thomson learning.
- Guerra Santin, O., Itard, L., & Visscher, H. (2009). The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock. *Energy and Buildings*, 41(11), 1223–1232. <https://doi.org/10.1016/j.enbuild.2009.07.002>
- Hanley, S. (2018). Never miss a cleantech update. Retrieved 3 February 2019, from <https://cleantechnica.com/2018/08/21/energy-vault-proposes-an-energy-storage-system-using-concrete-blocks/>
- Harmsen, D. (2011). *Trigeneration*. University of the Netherlands Antilles.
- Harrington, L., & Foster, R. (2008). *Energy Use in the Australian Residential Sector 1986-2020*. Retrieved from <http://www.industry.gov.au/Energy/Energy-information/Documents/energyuseaustralianresidentialsector19862020part1.pdf>
- Heinberg, R. (2010). What Is Sustainability? *The Post Carbon Reader: Managing the 21st Century's Sustainability Crises*, 1–9. Retrieved from <https://assets-production-webvanta-com.s3-us-west-2.amazonaws.com/000000/03/97/original/Reader/PCReader-Heinberg-Foundation.pdf> <http://www.postcarbon.org/publications/what-is-sustainability/>

- HEN. (2014). National Report of Curaçao. *The Third International Conference on Small Island Developing States*, (June), 27.
- Hernández-Santoyo, J., & Sánchez-Cifuentes, A. (2003). Trigeneration: An alternative for energy savings. *Applied Energy*, 76(1–3), 219–227. [https://doi.org/10.1016/S0306-2619\(03\)00061-8](https://doi.org/10.1016/S0306-2619(03)00061-8)
- Hordesky, & Micheal F. (2004). *Dictionary of Energy Efficiency Technologies*. (M. Dekker, Ed.) (First). New York.
- Hori, S., Kondo, K., Nogata, D., & Ben, H. (2013). The determinants of household energy-saving behavior: Survey and comparison in five major Asian cities. *Energy Policy*, 52, 354–362. <https://doi.org/10.1016/j.enpol.2012.09.043>
- International Energy Outlook 2016*. (2016). Washington. Retrieved from [https://www.eia.gov/outlooks/ieo/pdf/0484\(2016\).pdf](https://www.eia.gov/outlooks/ieo/pdf/0484(2016).pdf)
- Irving, M. (2018). Energy Vault to build grid-level, gravity-fed battery from a tower of concrete blocks. Retrieved 3 April 2019, from <https://newatlas.com/energy-vault-concrete-tower-battery/57164/>
- Jamaludin, N., Khamidi, M. F., Wahab, S. ngah A., & Klufallah, M. M. A. (2014). Indoor Thermal Environment in Tropical Climate Residential Building. *E3S Web of Conferences*, 3, 01026. <https://doi.org/10.1051/e3sconf/20140301026>
- Jungbluth, N., Tuchschnid, M., & de Wild-Scholten, M. (2008). Life Cycle Assessment of Photovoltaics: Update of ecoinvent data v2. 0. *ESU-Services Ltd.*, 2008, 1–22. <https://doi.org/10.1557/PROC-1041-R01-03>
- Kelman, I. and West, J.F. (2009) Climate change and Small Island Developing States: a critical review, *Ecological and Environmental Athropology*, Vol. 5, no. 1, <http://anthropology.uga.edu/>
- Kinney, R., Crucitti, P., Albert, R., & Latora, V. (2005). Modeling cascading failures in the North American power grid. *European Physical Journal B*, 46(1), 101–107. <https://doi.org/10.1140/epjb/e2005-00237-9>
- Kitio, V., Butera, F. M., Adhikari, R., & Aste, N. (2014). *SUSTAINABLE*

BUILDING Principles and Applications for Eastern Africa.

- Klemick, H., Kopits, E., & Wolverton, A. (2015). *The Energy Efficiency Paradox: A Case Study of Supermarket Refrigeration System Investment Decisions*. Pennsylvania, Washington.
- Koetsier, J. (2019). This Dutch Startup Converts Heat Into Cold Via A Stirling Engine, And Could Just Save The Planet. Retrieved from <https://www.forbes.com/sites/johnkoetsier/2019/01/18/this-dutch-startup-converts-heat-into-cold-via-a-stirling-engine-and-could-just-save-the-planet/#1904b8bb6744>
- Kreith, F., & Goswami, D. Y. (2008). *Energy management and conservation handbook*. New York: CRC Press Taylor & Francis group, LLC.
- Kresteniti, A. (2017). Development of a Concept for Energy Optimization of Existing Greek Hotel Buildings. *Procedia Environmental Sciences*, 38, 290–297. <https://doi.org/10.1016/j.proenv.2017.03.080>
- Kuhlman, T., & Farrington, J. (2010). What is sustainability? *Sustainability*, 2(11), 3436–3448. <https://doi.org/10.3390/su2113436>
- Kwidama, R. (2018). *Saving energy*. University of Curaçao.
- La Revolucion Energetica: Cuba's Energy Revolution. (2009). Retrieved from <http://www.renewableenergyworld.com/rea/news/article/2009/04/la-revolucion-energetica-cubas-energy-revolution>
- Latha, P. K., Darshana, Y., & Venugopal, V. (2015). Role of building material in thermal comfort in tropical climates - A review. *Journal of Building Engineering*, 3, 104–113. <https://doi.org/10.1016/j.jobbe.2015.06.003>
- Lebot, B., Agency, I. E., Meier, A., & Anglade, A. (2000). Global Implications of Standby Power Use.
- Ledwereld. (2018). Led T1 buizen. Retrieved 2 Februari 2018, from <https://www.ledwereld.nl/pcat/led-t1-buizen/>
- Liu, F., Meyer, A., & Hogan, J. (2010). *Mainstreaming Building Energy Efficiency Codes in Developing Countries: Global Experiences and Lessons from Early*

Adopters (First). Washington: World Bank.

- Liu, X., Kent Hoekman, S., Robbins, C., & Ross, P. (2015). Lifecycle climate impacts and economic performance of commercial-scale solar PV systems: A study of PV systems at Nevada's Desert Research Institute (DRI). *Solar Energy*, 119, 561–572.
<https://doi.org/10.1016/j.solener.2015.05.001>
- Lund, H. (2007). Renewable energy strategies for sustainable development. *Energy*, 32(6), 912–919. <https://doi.org/10.1016/j.energy.2006.10.017>
- Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems-The case of Denmark in years 2030 and 2050. *Energy*, 34(5), 524–531.
<https://doi.org/10.1016/j.energy.2008.04.003>
- Mahlia, T. M. I., Saktisahdan, T. J., Jannifar, A., Hasan, M. H., & Matseelar, H. S. C. (2014). A review of available methods and development on energy storage; Technology update. *Renewable and Sustainable Energy Reviews*, 33, 532–545. <https://doi.org/10.1016/j.rser.2014.01.068>
- Mallick, F. H. (1996). Thermal comfort and building design in the tropical climates. *Energy and Buildings*, 23(3), 161–167.
[https://doi.org/10.1016/0378-7788\(95\)00940-X](https://doi.org/10.1016/0378-7788(95)00940-X)
- Martha, A. (2011). Energy saving in homes and offices on the island Curaçao. University of Curaçao.
- Marugg, C. (2016). *HOW ENERGY EFFICIENT ARE CURAÇAOAN SUPERMARKETS AND SHOPPING MALLS?* University of Twente.
- Meier, A., Berkeley, L., & Nordman, B. (2007). Standby Energy : building a coherent international policy framework – moving to the next level. *Stockholm: European Council for an Energy Efficient Economy*, (March), 1–15.
- Meier, A. K. (2001). A worldwide review of standby power use in homes. *Lawrence Berkeley National Laboratory*, 1–5. Retrieved from <http://escholarship.org/uc/item/03m799xz.pdf>

- Meier, A., Lin, J., Liu, J., & Li, T. (2004). Standby power use in Chinese homes. *Energy and Buildings*, 36(12), 1211–1216.
<https://doi.org/10.1016/j.enbuild.2003.10.011>
- Meijer, A., Huijbregts, M. A. J., Schermer, J. J., & Reijnders, L. (2003). Life-cycle assessment of photovoltaic modules: Comparison of mc-Si, InGaP and InGaP/mc-Si solar modules. *Progress in Photovoltaics: Research and Applications*, 11(4), 275–287.
<https://doi.org/10.1002/pip.489>
- Milieu Centraal (n.d.). Energiezuinig verlichten: kies led. Retrieved 2 Februari 2018, from <https://www.milieucentraal.nl/energie-besparen/apparaten-en-verlichting/energiezuinig-verlichten-kies-led/>
- Meteorological Department Curacao Climatological Summary*. (2018). Willemstad, Curacao.
- Mylona, Z., Kolokotroni, M., & Tassou, S. A. (2017). Frozen food retail: Measuring and modelling energy use and space environmental systems in an operational supermarket. *Energy and Buildings*, 144, 129–143.
<https://doi.org/10.1016/j.enbuild.2017.03.049>
- Niles, K., & Lloyd, B. (2014). Using power sector reform as an opportunity to increase the uptake of renewable energy in the power sector: Responding to peak oil and climate change in Caribbean and Pacific small island developing States, between 1970-2010. *Natural Resources Forum*, 38(1), 14–26. <https://doi.org/10.1111/1477-8947.12031>
- Nucapital Curaçao bv. (n.d.). Retrieved from <http://nucapitalsvcs.com/>
- OAS (2013), Energy-efficiency guidelines for office buildings in tropical climate, General Secretariat of the Organization of American States, OEA/Ser.D/XXIII.15, Washinton, 186 pp
- Omega Engineering Inc. (2018). Owac systems. Retrieved 9 Februari 208, from <http://www.owacsystems.com/>
- Önüt, S., & Soner, S. (2006). Energy efficiency assessment for the Antalya Region hotels in Turkey. *Energy and Buildings*, 38(8), 964–971.
<https://doi.org/10.1016/j.enbuild.2005.11.006>

- Ouyang, J., & Hokao, K. (2009). Energy-saving potential by improving occupants' behavior in urban residential sector in Hangzhou City, China. *Energy and Buildings*, 41(7), 711–720. <https://doi.org/10.1016/j.enbuild.2009.02.003>
- Owen, A. L., & Videras, J. (2006). Civic cooperation, pro-environment attitudes, and behavioral intentions. *Ecological Economics*, 58(4), 814–829. <https://doi.org/10.1016/j.ecolecon.2005.09.007>
- Oyewunmi, O. A., Pantaleo, A. M., & Markides, C. N. (2017). ScienceDirect ScienceDirect ORC cogeneration systems in waste-heat recovery applications Assessing the feasibility of using the heat demand-outdoor temperature function for a long-term district heat demand forecast. *Energy Procedia*, 142, 1736–1742. <https://doi.org/10.1016/j.egypro.2017.12.557>
- Pakula, C., & Stamminger, R. (2015). Energy and water savings potential in automatic laundry washing processes, 205–222. <https://doi.org/10.1007/s12053-014-9288-0>
- Parkes, R. (2017). Biomethane : green gas rising ? Reinforced Plastics, 18(April), 33–35. <https://doi.org/10.1016/j.ref.2017.02.003>
- Peters, R., & Burda, C. (2007). The Basic on Base Load: Meeting Ontario's Base Load Electricity Demand with Renewable Power Sources. Ontario.
- Piconi, R., Pedretti, A., Kerr, M., Fyke, A., & Gross, B. (n.d.). Ground-breaking energy storage technology. Retrieved 3 April 2019, from <https://energyvault.ch/>
- Placet, M., Katipamula, S., Liu, B., Dirks, J., Xie, Y., Sullivan, G., & Solutions, E. (2010). Energy End-Use Patterns in Full-Service Hotels : A Case Study Background on the Project. *ACEEE Summer Study on Energy Efficiency in Buildings*, 310–324. Retrieved from <http://aceee.rste040v1mp01.blackmesh.com/files/proceedings/2010/data/papers/1984.pdf>
- Policy Document Regulation Electricity Supply Curaçao 2011-2015. (2011),

(February 2011).

- Pope, J., Annandale, D., & Morrison-Saunders, A. (2004). Conceptualising sustainability assessment. *Environmental Impact Assessment Review*, 24(6), 595–616. <https://doi.org/10.1016/j.eiar.2004.03.001>
- Prudenzi, A., Silvestri, A., Lamedica, R., Falvo, M. C., Grasselli, U., & Regoli, M. (2011). Standby power end users and their demand management impact on household's load shape. *IEEE Power and Energy Society General Meeting*, 1–6. <https://doi.org/10.1109/PES.2011.6039526>
- Rattanongphisat, W., & Rordprapat, W. (2014). Strategy for energy efficient buildings in tropical climate. *Energy Procedia*, 52, 10–17. <https://doi.org/10.1016/j.egypro.2014.07.049>
- Reardon, C., & Clarke, D. (2013). *Passive cooling*.
- Reich, N. ., Alsema, E. ., van Sark, W. G. J. H. ., & Nieuwlaar, E. (2007). CO₂ emissions of PV in the perspective of a renewable energy economy. Utrecht.
- Reinders, a, Verlinden, P., van Sark, W., & Freundlich, a. (2017). Photovoltaic Solar Energy: From Fundamentals to Applications, 5. Retrieved from <https://books.google.fi/books?id=u73VDQAAQBAJ>
- Renewables 2018: Global status report. REN21 (2018). Athens
- Rodriguez-Ubinas, E., Montero, C., Porteros, M., Vega, S., Navarro, I., Castillo-Cagigal, M., ... Gutiérrez, A. (2014). Passive design strategies and performance of Net Energy Plus Houses. *Energy and Buildings*, 83, 10–22. <https://doi.org/10.1016/j.enbuild.2014.03.074>
- Sadeghi, A., & Larimian, T. (2018). Sustainable electricity generation mix for Iran : A fuzzy analytic network process approach. *Sustainable Energy Technologies and Assessments*, 28(December 2016), 30–42. <https://doi.org/10.1016/j.seta.2018.04.001>
- Sahin, M. C., & Aydinalp Koksall, M. (2014). Standby electricity consumption and saving potentials of Turkish households. *Applied Energy*, 114, 531–538. <https://doi.org/10.1016/j.apenergy.2013.10.021>

- Sahin, M. C., Gugul, G. N., & Koksai, M. A. (2011). Determining Appliance Standby Electricity Consumption for Turkish Households, 276–288.
- Saidur, R. (2009). Energy consumption, energy savings, and emission analysis in Malaysian office buildings. *Energy Policy*, 37(10), 4104–4113. <https://doi.org/10.1016/j.enpol.2009.04.052>
- Shieber, J. (2018). The cost of energy storage has stalled adoption of renewable power. Retrieved from <https://techcrunch.com/2018/11/07/the-cost-of-energy-storage-has-stalled-adoption-of-renewable-power-energy-vault-has-a-solution/>
- Shiming, D., & Burnett, J. (2002). Energy use and management in hotels in Hong Kong. *International Journal of Hospitality Management*, 21, 371–380. [https://doi.org/10.1016/S0278-4319\(02\)00016-6](https://doi.org/10.1016/S0278-4319(02)00016-6)
- Shuma-iwisi, M. V. (2009). Estimation of Standby Power and Energy Losses in South African Homes, (October), 217.
- Singh, R. K., Murty, H. R., Gupta, S. K., & Dikshit, A. K. (2009). An overview of sustainability assessment methodologies. *Ecological Indicators*, 9(2), 189–212. <https://doi.org/10.1016/j.ecolind.2008.05.011>
- Skystream 3.7. (2010). Retrieved 10 November 2015, from <http://www.windenergy.com/products/skystream/skystream-3.7>
- Solanki, P. S., Mallela, V. S., & Zhou, C. (2013). An investigation of standby energy losses in residential sector: Solutions and policies. *International Journal of Energy and Environment*, 4(1), 117–126.
- Sorknaes, P., Maeng, H., Weiss, T., & Anderson, A. N. (2013). *Overview of the Danish Power system and RES integration*.
- Spector, J. (2018). Can newcomer Energy Vault break the curse of mechanical grid storage? Retrieved 3 April 2019, from <https://www.greentechmedia.com/articles/read/energy-vault-stacks-concrete-blocks-to-store-energy#gs.4j30gd>
- States, O. of A. (2013). Energy Efficiency Guidelines for Office Buildings in Tropical Climate., (February 2013), 27. Retrieved from

http://ecpamericas.org/data/files/Events/Saint Lucia Presentations/DGB.5-ExecutiveSummary_updated.pdf

- Sugiarta, N., Tassou, S. A., Chaer, I., & Marriott, D. (2009). Trigeneration in food retail : An energetic , economic and environmental evaluation for a supermarket application. *Applied Thermal Engineering*, 29(13), 2624–2632. <https://doi.org/10.1016/j.applthermaleng.2008.11.018>
- Technologies for Sustainability Systems. (2018). Retrieved 12 August 2018, from <https://www.e-education.psu.edu/eme807/node/667>
- Timilsina, G.R. and Shah, K.U. (2016) Policy supports and interventions for scaling up renewable energy development I Small Island developing States, *Energy Policy*, Vol. 98, pp. 653-662.
- Thomson, R. C., Harrison, G. P., & Chick, J. P. (2017). Marginal greenhouse gas emissions displacement of wind power in Great Britain. *Energy Policy*, 101(May 2016), 201–210. <https://doi.org/10.1016/j.enpol.2016.11.012>
- Strategies for sustainable long term economic development in Curaçao*. (2013). Willemstad, Curaçao.
- Sumper, A., Robledo-García, M., Villafáfila-Robles, R., Bergas-Jané, J., & Andrés-Peiró, J. (2011). Life-cycle assessment of a photovoltaic system in Catalonia (Spain). *Renewable and Sustainable Energy Reviews*, 15(8), 3888–3896. <https://doi.org/10.1016/j.rser.2011.07.023>
- Tang, M., Fu, X., Cao, H., Shen, Y., Deng, H., & Wu, G. (2016). Energy performance of hotel buildings in Lijiang, China. *Sustainability (Switzerland)*, 8(8). <https://doi.org/10.3390/su8080780>
- Tantasavasdi, C., Srebric, J., & Chen, Q. (2001). Natural ventilation design for houses in Thailand. *Energy and Buildings*, 33(8), 815–824. [https://doi.org/10.1016/S0378-7788\(01\)00073-1](https://doi.org/10.1016/S0378-7788(01)00073-1)
- Ter-Gazarian, A. G. (2011). *Energy storage for power systems* (Second). London: The Institution of Engineering and Technology.
- The International Energy Agency IEA. (2015). Key World Energy, 82.

<https://doi.org/http://dx.doi.org/10.1787/weo-2011-en>

Turn waste heat into profit. (2019). Retrieved from <https://www.soundenergy.nl/>

Tracking Clean Energy Progress 2013. (2013). Paris, France. Retrieved from www.iea.org

Trinidad, Q. (2015). *Standby loss op Curaçao*. University of Curaçao.

Tseleki, K. (2012). *Energy savings potential from simple standby reduction devices in the Netherlands*. University of Utrecht.

Uk Government GHG Conversion Factor for company reporting. (2018)

UNEP, UN DSEA, FAO (2012) SIDS-focused green economy: An analysis of challenges and opportunities. (www.unep.org/greeneconomy) and (www.unep.org/regionalseas).

United Nations Brundtland 1987. (n.d.).

UN (United Nations), (2005) Draft Mauritius Strategy for the further implementation of the programme of action for the sustainable development of Small Island Developing States. Document A/CONF.207/CRP.7, 13 January 2005; from the International meeting to review the implementation of the programme of action for the sustainable development of Small Island Developing States. Port Louis, Mauritius: UN (United Nations), 10-14 January 2005.

United Nations (1992) Specific problems and needs of island developing countries, General Assembly A/47/414 (New York: UN, 1992)

UN (United Nations), (1994) Report of the global conference on the sustainable development of small island developing states. Document A/CONF.167/9, October, 1994; from the Global Conference on the Sustainable Development of Small Island Developing States. Bridgetown: UN (United Nations), 25 April – 6 May 1994.

UN. (2014). Samoa Pathway-outcome. Retrieved 5 June 2018, from <http://www.sids2014.org/index.php?menu=1586>

- United Nations Framework Convention on Climate Change [UNFCCC]. (2015). Paris Agreement. Paris Agreement, 25. <https://doi.org/FCCC/CP/2015/L.9>
- UN-OHRLLS (2012) Small Island, Bigger Stakes, Office of the High representative for the least developed countries and Landlocked developing countries, and small island developing states, 32 pp. <http://unohrrls.org/custom-content/uploads/2013/11/SIDS-Advocacy-Booklet.pdf>
- User's manual digital power meter KPM1000.* (2011). Southwood, Japan.
- van Alphen, K., Hekkert, M. P., & van Sark, W. G. J. H. M. (2008). Renewable energy technologies in the Maldives-Realizing the potential. *Renewable and Sustainable Energy Reviews*, 12(1), 162–180. <https://doi.org/10.1016/j.rser.2006.07.006>
- Van Raaij, W. F., & Verhallen, T. M. M. (1983). A behavioral model of residential energy use. *Journal of Economic Psychology*, 3(1), 39–63. [https://doi.org/10.1016/0167-4870\(83\)90057-0](https://doi.org/10.1016/0167-4870(83)90057-0)
- Varho, V., Winquist, E., & Rikkonen, P. (2019). Is biogas an energy or a sustainability product? - Business opportunities in the Finnish biogas branch, 233, 1344–1354. <https://doi.org/10.1016/j.jclepro.2019.06.181>
- Vittal, V. (2010). The Impact of Renewable Resources on the Performance and Reliability of the Electric Grid. *The Bridge*, 40(1), 1–4. <https://doi.org/10.1038/138611c0>
- Volpi, G., Dourado, R., & Gomes, M. (2006). A sustainable electricity blueprint for Brazil. *Energy for Sustainable Development*, 10(4), 14–24. [https://doi.org/10.1016/S0973-0826\(08\)60552-9](https://doi.org/10.1016/S0973-0826(08)60552-9)
- Wang, J. C. (2012). A study on the energy performance of hotel buildings in Taiwan. *Energy and Buildings*, 49, 268–275. <https://doi.org/10.1016/j.enbuild.2012.02.016>
- Wang, Z., Zhang, B., Yin, J., & Zhang, Y. (2011). Determinants and policy implications for household electricity-saving behaviour: Evidence from Beijing, China. *Energy Policy*, 39(6), 3550–3557.

<https://doi.org/10.1016/j.enpol.2011.03.055>

War, J. C. (2011). Seawater Air Conditioning (Swac) a Renewable Energy Alternative. *Oceans 2011*, 1–9.

WEC 2012 Energy Efficiency Policies around the World. (n.d.).

Weisser, D. (2004). On the economics of electricity consumption in small island developing states: A role for renewable energy technologies? *Energy Policy*, 32(1), 127–140. [https://doi.org/10.1016/S0301-4215\(03\)00047-8](https://doi.org/10.1016/S0301-4215(03)00047-8)

Wellinger, A., Murphy, J., & Baxter, D. (2013). *The biogas handbook: Science, production and applications*. Oxford: Springer.

Wong, N. H., Feriadi, H., Lim, P. Y., Tham, K. W., Sekhar, C., & Cheong, K. W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment*, 37(12), 1267–1277. [https://doi.org/10.1016/S0360-1323\(01\)00103-2](https://doi.org/10.1016/S0360-1323(01)00103-2)

Yue, T., Long, R., & Chen, H. (2013). Factors influencing energy-saving behavior of urban households in jiangsu province. *Energy Policy*, 62, 665–675. <https://doi.org/10.1016/j.enpol.2013.07.051>

Abbreviations

AC	Alternate Current
BOS	Balance of System
BTPU	Bureau Telecommunicatie Post en Utiliteit
CRU	Curaçao Refinery Utilities
CSD	Commission of Sustainable Development
DC	Direct Current
ERES	Environmentally Responsible Economics
GHG	Global greenhouse gas
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
IUH	Integrated Utility Holding
KAE	Kompania di Awa y Elektrisidat
KODELA	Kompania di Distribushon di Elektrisidat
LCA	Life Cycle Analysis
LED	Light-emitting Diode
MPPT	Maximum Power Point Tracking
NIGM	Nederlands Indisch Gas Maatschappij
OECD	Economic Co-operation and Development
OGEM	Overzeese Gas en Elektriciteit Maatschappij
OWAC	Ocean Water Assisted Cooling
PG&E	Pacific Gas and electric
PSH	Peak Sun Hour
PV	Photovoltaic
R&D	Research and Development
RESs	Renewable energy sources
RFI	Reflective foil insulation
SAM	Sustainability Assessment Model
SIDS	Small Island Developing States
SWAC	Seawater Air Conditioning
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WEC	World Energy Council

Appendix I: Small wind turbines in Curaçao

This Appendix provides the details of the electricity production of three small wind turbines (Inecia, 2013).

Table AI: Production of three small wind turbines in Curaçao

Project 2012	Production [kWh]
1	3423.17
2	1961.61
3	1773

All three wind turbines are of the type ‘Skystream 3.7’ (Figure AI). The rated capacity of these turbines is 2.7 kW, and they are designed for homes and businesses. They are also the first wind turbines in which all the controls and inverters are built in. The manufacturer expected that these wind turbines would generate approximately 400 kWh per month (‘Skystream 3.7’, 2010). The total production of the three wind turbines in Curaçao is between 147 and 285 kWh/month.

Figure AI: The Skystream wind turbine

Appendix 2: Survey questions energy use by households in Curaçao

1. Would you like to join this survey?
2. What is the total monthly gross household income of your household?
 - a. Nafl. 0 -2,000
 - b. Nafl. 2,001 – 5,000
 - c. Nafl. 5,001 +
3. How many persons live in your house?
4. Do you take actions to save energy?
5. If the answer is yes, why do you save energy?

If the answer is no, why do you not save energy?
6. If the answer is yes. How do you save energy?
7. What types of appliances do you have in your house?
8. How many appliances? (each appliance)
9. What types of indoor lightings do you have in your house?
10. How many indoor lightings do you have?
11. What types of outdoor lightings do you have?
12. How many outdoor lightings do you have?

Appendix 3: Survey questions energy use by office buildings in Curaçao

1. Would you like to join this survey?
2. To which category does your company belong?
 - a. Micro business group
 - b. Small business group
 - c. Middle business group
 - d. Large business group
3. Do your company take actions to save energy?
4. If the answer is yes, why do your company save energy?

If the answer is no, why do your company not save energy?
5. If the answer is yes. How do your company save energy?
6. What types of appliances do your company have?
7. How many appliances? (each appliance)
8. What types of indoor lightings do your company have?
9. How many indoor lightings do your company have?
10. What types of outdoor lightings do your company have?
11. How many outdoor lightings do your company have?

Appendix 4: Results energy use by hotels in Curaçao

Table A2: Energy use by hotels in Curaçao

Hotels	No. of rooms	Total [kWh/year]
A	28	282753
B	80	303792
C	23	354600
D	150	1057689
E	155	790184
F	204	1255104
G	98	607825
H	25	86698
I	17	162963
J	21	122483
K	60	284540
L	21	130582
M	24	146851
N	30	176224
O	341	788691
P	41	179758
Q	82	553438
R	196	1070167
S	237	1239438
T	72	465157
U	210	539779
V	137	414787
<i>Total</i>	2252	11013502

Appendix 5: Results energy use by supermarkets in Curaçao

Table A3: Energy use by Supermarkets in Curaçao

Supermarket	Total [kWh/year]
S1	545698
S2	596136
S3	621069
S4	715363
S5	714606
S6	799037
S7	815405
S8	929748
S9	1041314
<i>Total</i>	<i>6778377</i>

Appendix 6: Survey questions to measure standby power losses in Curaçao

1. What is standby consumption?
2. Do you switch off your computer, when you are not using it?
3. Do you use power strip to switch off your computer, and printer, when they are not performing their main task?
4. How much time do you use your computer per day?
5. Do you unplug the charger of your laptop, when you are not using the laptop?
6. How much time do you spend on your laptop per day?
7. Do you unplug the charger(s) of your telephone, when it is not in use?
8. Do you unplug your printer when you are not using it?
9. How much time do you use your printer per day?
10. Do you unplug your wireless router when it is not performing its main task?
11. How much time do you use the wireless router per day?
12. Do you unplug your microwave, when you are not using it?
13. How much time do you use the microwave per day?
14. Do you unplug your television and decoder when they are not performing their main task?
15. How much time do you watch the television per day?
16. Do you unplug your stereo set/radio when it is not performing its main task?
17. How much time do you listen to your radio per day?

Appendix 7a: Energy savings potential

Residential										
NO		Demand [Gwh]	Breakdown [%]	Demand/ breakdown [GWh]	% of the residents will save energy	Savings potential of the appliances [%]	Savings potential appliances [GWh]	Savings behaviour	Savings through building eff	Savings potential total [GWh]
		331.12488								
1	Air conditioners		23.0%	72.84747417	70%	40.0%	20.39729277	2.768204	7.284747417	30.4502442
2	Lighting systems		28.0%	92.71496713	70%	85% & 66%	52.20594369	1.854299		54.06024303
3	Refrigerators/ freezers		22.1%	73.17859905	70%	50.0%	25.61250967	1.463572		27.07608165
	Total		73.10%	238.7410404			98.21574613	6.08608	7.284747417	111.5865689
Commercial										
		Demand [GWh]	Breakdown [%]	Demand/ breakdown [GWh]	% of the commercials will save	Savings potential of the appliances [%]	Savings potential appliances [GWh]	Savings behaviour	Savings through building eff	Savings potential total [GWh]
		169.48692								
4	Air conditioners		53.9%	91.35345082	70%	40.0%	25.57896623	3.471431	9.135345082	38.18574244
5	Lighting systems		23.0%	38.981992	70%	66.0%	18.0096803	0.77964	0.38981992	19.17914006
6	Refrigerators/ freezers		1.4%	2.372816904	70%	50.0%	0.830485917	0.047456		0.877942255
	Total		78.3%	132.7082597			44.41913245	4.29853	9.525165002	58.24282476

Appendix 7b (continued): Energy savings potential

Standard industries									
	Demand [GWh]	Breakdown [%]	Demand/ breakdown [GWh]	% of the industries will save	Savings potential of the appliances [%]	Savings potential appliances [GWh]	Savings behaviour	Savings through building eff	Savings potential total [GWh]
7	102.83151	27.0%	28.79282238	100%	20.0%	5.758564476	1.094127	2.879282238	9.731973964
8		21.0%	24.67956204	100%	20.0%	4.935912408	0.493591	0.24679562	5.676299269
9		32.0%	32.90608272	20%	30.0%	1.974364963	0.658122		2.632486617
		80.0%	86.37846714			12.66884185	2.24584	3.126077858	18.04075985
Export industries									
	Demand [GWh]	Breakdown [%]	Demand/ breakdown [GWh]	% of the industries will save	Savings potential of the appliances [%]	Savings potential appliances [GWh]	Savings behaviour	Savings through building eff	Savings potential total [GWh]
10	111.16559	41.0%	45.57789073	50%	65.0%	14.81281449	1.73196	4.557789073	21.10256341
11		15.0%	16.67483807	100%	20.0%	3.334967614	0.333497	0.166748381	3.835212756
12		20.0%	22.23311743	100%	50.0%	11.11655871	0.444662		
		76.0%	84.48584623			29.26434082	2.51012	4.724537454	36.49899723

Appendix 7c (continued): Energy savings potential

Street lighting										
		Demand [GWh]	Breakdown [%]	Demand/ breakdown [GWh]	% of the street light will be replaced	Savings [%]	Savings potential appliances [GWh]	Savings behaviour	Savings through building eff	Savings potential total [GWh]
		8.0047182								
13	Lighting systems		100%	8.004718199	100%	50%	4.0023591			4.0023591
	Total			8.004718199			4.0023591			4.0023591
	Total						188.5704203	15.1406	24.66052773	228.3715098

Appendix 8: Expected electricity demand in Curaçao (2014-2033)

Acknowledgement

After an intensive learning period of various years, now, I have a good feeling for both completing my PhD research, and for the opportunity to express my heartfelt gratitude to everyone who contributed to this research. Furthermore, a feeling of thankfulness to God, who gives me health and knowledge to do my everyday work and to conduct this PhD research.

My sincere gratitude goes to Prof. dr. ir. Joop Halman, who supervised and helped me in this research process. Besides, this research process, you always advised me how to combine this research with my everyday work. I truly appreciate it. Thank you very much for your patience and being my supervisor. This PhD research would not have been completed without your thorough guidance and support.

Dr. Silu Bhochhibhoya, thank you very much for your supervision of this research process and your motivations through the last phase of this research process.

Special thanks go also to Dr. Bram Entrop, who supervised a great part of this research process. Your experience regarding sustainability helped me a lot through this research process.

I am very grateful to all the students who contributed to this research process: Anethy Martha, Quentin Trinidad, Rensley Kwidama, Guus van Eldic, and Caithlin Marugg.

I would like to thank my colleagues of the University of Curaçao, especially our Dean Ergün Erkoçu, Naidison Bregitha, Tamara van Aerde, Louella Blijden-Boelbaai, Idelca Jansen-Raphaëla, and Rugiabertha Serboni for their support and motivation through this research process. I further appreciate the support and facilities that were provided by the University of Twente.

I am also indebted to Schlumberger for providing the funds to my research through the chair Technology for Sustainable Development at the University of Curaçao.

All my love and thanks go to my beloved wife, Kirsten Bulbaai van Wijngaarden, my daughters Marjolein, Larisa, and Roselyn Bulbaai, for their patience and support through this research process. I am highly indebted to my wife Kirsten for her endurance, encouragement and continuous support during the past period. She took a great part of the care and education of our daughters into her hands. Last but not least, I would like to thank my beloved mother Elsa Bulbaai for her patience and support through this research process.

About the author

Richenel Bulbaai was born on Curaçao on December 13, 1967. After having finished

Secondary school in 1986, he studied electrical engineering (BSc) at the University of Curaçao (UoC), where he graduated in 1990. He continued his studies in electrical engineering at Eindhoven University of Technology, where he obtained his MSc in 1995. In 1997, he joined UoC's Faculty of Engineering as a lecturer in the department of electrical engineering where he specialized himself in the areas of Information Technology & Electrical Systems. He combined this work with a study in Business Administration at the UoC and obtained his MBA in 2006. From 2007-2013 he also served as the dean of the Faculty of Engineering at UoC.

Richenel is professionally particularly interested in the fields of renewable energy, energy efficiency and information technology. He teaches Renewable energy; Energy efficiency; Electrical networks; Mathematics; Engineering & society; Research design and research methods, Electrical power systems and; Symmetrical components in the electric grid. He has supervised more than 100 BSc students and several MBA thesis projects on areas such as energy-saving, renewable energy, waste management, and electrical power systems. In 2017, he was appointed by the Government as a member of the Supervisory board at Aqualectra, the Water and Electricity production and distribution company in Curaçao. He combined this membership of the Supervisory board and his work in teaching and supervising students at the University of Curaçao with conducting this PhD study. Richenel Bulbaai is married and has three daughters.

RICHENEL BULBAAI

TOWARD 100% SUSTAINABLE ENERGY PRODUCTION

In this study an analysis is first made of the energy saving potential for Curaçao. This analysis has been made for both supply-side electricity production as well as demand-side energy use. Based on the analysis, a wide array of options are proposed through which Curaçao can not only drastically reduce its demand-side energy use but also the fuel used on the supply side to the energy demands. In the third part of this study an approach is developed through which Curaçao but also other Small Island Developing States can achieve a fully sustainable energy production system based on wind, solar, and biogas as the only energy sources.

Implementation of the findings and suggested approaches included in this PhD thesis will change Curaçao, by 2033, into an island whose electricity plants are based on a fully sustainable energy production system. In addition, implementing the proposed roadmap to achieve a sustainable energy production system in Curaçao will reduce CO² emissions by approximately 92%.