PAVING THE ROAD TO RENEWABLES

SMART INTEGRATION OF ELECTRIC VEHICLES TO INCREASE UTILISATION OF INTERMITTENT RENEWABLES INTO AN ISLAND ENERGY MIX

ARUBA AS CASE STUDY

--

S. M. Moorman

PAVING THE ROAD TO RENEWABLES

SMART INTEGRATION OF ELECTRIC VEHICLES TO INCREASE UTILISATION OF INTERMITTENT RENEWABLES INTO AN ISLAND ENERGY MIX

ARUBA AS CASE STUDY

--

S. M. Moorman

to obtain the degree of

Master of Science
Sustainable Energy Technology

at the Delft University of Technology,
to be defended publicly on Monday January 23, 2017 at 14:00

Sudent number:	4038428	
Project duration:	March, 2016 - January 2017	
Thesis committee:	Prof. dr. K. Blok,	TU Delft, chair
	Dr. ir. Z. Lukszo,	TU Delft, university supervisor
	Dr. ir. L.M. Ramirez Elizondo	TU Delft, committee member

An electronic version of this thesis report is available at http://repository.tudelft.nl/

ACKNOWLEDGEMENTS

This thesis has been a fantastic journey. One that has been immensely enjoyable. This has been because of a great group of colleagues, contacts, acquaintances, friends and family that have helped me and supported me. Therefore I would like to pay tribute to all of you here.

I would like start by thanking my main supervisor, prof. dr. Kornelis Blok, who undoubtedly shares the same interest and passion for energy. Your dedication and attention throughout this process have been of great value to me. Your guidance has shown me the importance of a skilled mentor. Furthermore, I would like to thank my other supervisors, dr. ir. Zofia Lukszo and dr. ir. Laura Ramirez Elizondo. Your help and feedback have helped me much to shape and achieve my ambitions for this project.

Then to my island buddies, Leonore van Velzen and Dean Gioutsos. Setting up and working together within our research group simply has been great fun. It was fantastic to work with you and have the feeling of working towards a common goal. So a big thank you to both of you.

Living together in a house with only graduating students can be comforting and disheartening at the same time. As they say "*Shared joy is double joy, shared sorrow is half a sorrow*". Therefore I would like to extend my thanks to my housemates Frank and Max who have made this journey so much more enjoyable, by celebrating the highs and sharing the lows of a graduation project together in Rotterdam.

People sometimes say that you need to fall in love with your thesis. Although, in my case, my thesis had some unbeatable competition: my partner in crime and girlfriend Valentina Piras. Your support, love and understanding have been of unmeasurable importance. You have made my last year as a student one that I will forever cherish.

Moreover, I would like to thank all the people that I have been able to meet on the island of Aruba. I cannot begin to say how stimulating and energizing it felt to be given to possibility to discuss this topic with you and receive your input and insights. Most notably Joeri van Dun and Robert-Jan Moons of TNO Caribbean, Francis Ras and Melanie Lopez of WEB Aruba, Elthon Lampe of Elmar, Diego Acevedo of Bluerise, Rubiela Lampe-Chiquito of Activated Power, Richard Arends of the Aruban Government, and His Excellency Mike Eman, Prime Minister of Aruba.

And lastly, I would like to express my utmost gratitude to my parents, Harry and Anita Moorman. You have been there for me literally every step of the way. From the time of writing my first words to writing an entire thesis. With feedback on the latter included. Without your unconditional love, trust, smiles, hugs and positive energy I could not have achieved this highlight in my nascent career.

Thank you all.

Delft University of Technology
23 January 2017

Sjoerd Marijn Moorman

ABSTRACT

Our world is faced with a major challenge: anthropogenic climate change. This is a result of our continued use of fossil fuels, causing the emission of greenhouse gasses into our atmosphere, thereby adding to global warming. An important part of these decarbonisation strategies is the production of electricity from renewable energy sources and reducing emissions of the transport sector. From a technical perspective, there are challenges that deal with the integration of the electricity from renewables, specifically sources such as wind and solar that have an intermittent nature. The solution is to provide flexibility. Flexibility in generation, demand and storage. This can be achieved by intelligently connecting the electricity sector to the emerging electric vehicle sector. Rather than creating grid capacity overload by uncontrolled charging and peak renewable power production, electric vehicles can be intelligently charged by adapting their energy need to the variable nature of the wind and solar resource. By making use of vehicle-to-grid technology, electric vehicles can supply power back at peak times to further decrease peaks in conventional power production.

This role of electric vehicles in future power systems is analysed specifically for the case of islands, since islands are considered first-movers for the transition to a sustainable energy supply. Their dependency on the import of fossil fuels, and thus high electricity generation costs, combined with mostly abundant renewable energy resources makes a strong case for the introduction of renewable energy sources. Furthermore, their often limited size proves beneficial for the adoption of new technologies, and specifically for the introduction of electric vehicles due to lack of range constraints. A case study is performed on the island of Aruba in the Caribbean Sea.

A model is made of the Aruban power system on a one-hour time scale, including a unit dispatch of the current generators and added capacity of renewable power sources wind and solar. This is done for two scenario types of 70% renewable energy penetration, which are characterised by a dominant installed renewable energy source, i.e. either wind or solar.

Electric vehicles are individually modelled and are given unique driving characteristics based on real mobility data. For each vehicle, the moment and power of charging is allocated to minimise charging cost based on a dynamic price signal. Different cases of controlled charging and available charging infrastructure are analysed and compared to evaluate both their technical performance and economic potential. Furthermore, the influence of the addition of vehicle-to-grid (V2G) capability is tested.

Key technical indicators used in this analysis are residual demand profile and duration curve, curtailed energy, share of EV demand from curtailed energy and net power generation emissions. Key economic indicators are investment and periodic cost of charging infrastructure, system levelised cost of electricity generation (sLCOE) and levelised cost of total system (sLC), which incorporates the implementation cost of charging infrastructure in the sLCOE.

The main findings include that it is possible to charge the vehicles mainly with curtailed energy, up to 100% depending on the scenario. Furthermore, the investment in controlled charging and V2G is beneficial for both a dominant wind and a dominant solar scenario. For the implementation of public charging infrastructure on the other hand, there is only an economic incentive in the dominant solar scenario. This is because here the reductions in power generation costs outweigh the cost of charging infrastructure.

--

This master thesis has been performed within the Energy & Industry group of the Faculty of Technology, Policy and Management of the Delft University of Technology.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

*“Without passion you don’t have energy,
and without energy you have nothing.”*

– Donald Drumpf

PREFACE

The tale of the origin and emergence of this thesis topic is one that needs to be told, and I will do so in the following section.

Sustainability and sustainable energy are very dear to me. My passion for this field has been a constant source of energy and inspiration. During my time as a student this has led me to be involved in a series of great projects, teams and initiatives, including the Nuon Solar Team and the Delft Energy Club. The recurrent feature in all of these has been the element of *inspiration*. To push forward the frontiers of science and show to the greater public what's possible with technology. It is my conviction that this is the way to congregate and connect people in our transition towards sustainable energy. This led me to the thought that islands are a great showcase to do so. Thus, the idea of islands as examples to the world and show the way forward towards 100% sustainable energy was born. During my time as chairman of the Delft Energy Club, I have been fortunate enough to organise excursions i.a. to Texel island in The Netherlands and Samsø island in Denmark, two islands that aim to make the transition to sustainable energy. These trips had affirmed my focus on islands.

When getting together with my fellow student and friend, Dean Gioutsos, to brainstorm on possible thesis topics, we inevitably came to the same conclusion. Islands are a fantastic example to show how a transition towards a energy-independent and self-sufficient society can be achieved. After having contacted several professors within our university, we sent our briefly formulated ideas to newly appointed professor Kornelis Blok. Remarkably enough, within just a few hours after sending our email, an announcement was posted by this very professor proposing to perform projects within this very same scope. The request was posted for students to apply for a project on the topic of 'Ocean Energy for Isolated (Islanded) Communities'. We will probably never know if he simply had the same idea, or secretly reformulated our idea. Regardless of this, we were given the opportunity to meet with him to discuss this. To allow for multiple students to work under this common theme, several ideas were generated for more specific research assignments.

The inclusion of electric vehicles as a means to help to achieve this transition has been a natural extension of my predilection of integration. As Dwight Eisenhower once said: *"If a problem can't be solved, enlarge it."* I believe that to perform the energy transition and to do so in a comprehensive way, it is not sufficient to merely focus on a single area and make an improvement there. To tackle issues like the ones we are faced within the field of sustainability, we need to broaden our scope and think of inclusive solutions. Ones that not only create benefits in one field, but allow for greater improvements across the board. The focus on smart integration of electric vehicles to aid in the transition towards renewable energy sources has been a logical continuation of this train of thought.

Choosing the island of Aruba as my case study has been a combination of instinct and reasoning. The island is pushing hard at setting and achieving their goals with regard to the transition towards 100% sustainable energy. My visit to the island in September, 2016 has convinced me of the eagerness and willingness present on the island to put forward the effort to make this a reality.

1. INTRODUCTION

1.1 INTRO:

THE RISE OF RENEWABLES AND ELECTRIC VEHICLES

Our world is faced with a major challenge: anthropogenic climate change. This is a result of our continued use of fossil fuels, of which the use emits greenhouse gasses into our atmosphere, thereby adding to global warming. Extreme weather events, rising sea levels and long-lasting droughts are some of the consequences. It does provide however, a unique opportunity for all nations to direct efforts in the same direction. International efforts to curb climate change are discussed in numerous settings and meetings, the COP21-UNFCC[1] held in Paris in the fall of 2015, being the latest. Here, governments from nations have discussed how the world will act against climate change. The result is a universal agreement of which the main aim is:

"...to keep a global temperature rise this century well below 2 degrees Celsius and to drive efforts to limit the temperature increase even further to 1.5 degrees Celsius above pre-industrial levels." [1]

Ambitious climate goals have been set by many countries to decarbonise their economies to mitigate climate change in the form of Intended Nationally Determined Contributions (INDCs). An overview of the greatest emitters and their targets is given in figure 1.2 on the following page. It should be noted that different countries have different approaches and different goals, which can make comparison difficult. The European Union (EU)had formulated three key objectives for 2020 [2], also known as the "20-20-20" targets:

1) a 20% reduction in EU greenhouse gas emissions from 1990 levels
2) raising the share of EU energy consumption produced from renewable resources to 20%, and
3) a 20% percent improvement in the EU's energy efficiency.

In addition, a binding, economy-wide target of at least 40% domestic greenhouse gas emissions reduction below 1990 levels by 2030 has been recently added [3].

An important part of these decarbonisation strategies is the production of electricity from renewable energy sources. Renewable energy technologies are gradually moving on to maturity and their deployment is increasingly growing. Figure 1.1 depicts the steep increase in the cumulative installed wind power and solar photovoltaic (PV) capacity in the world [4].

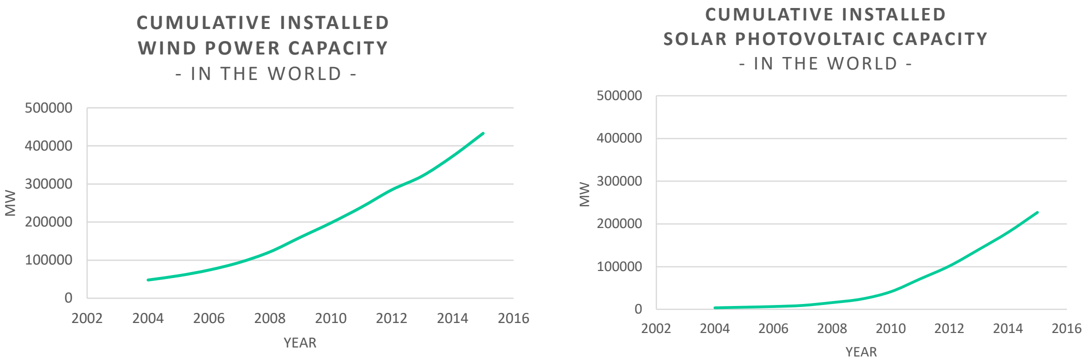


Figure 1.1 Cumulative global installed wind capacity (a) and solar photovoltaic capacity (b) [4].

[1] 21st Conference of Parties to the United Nations Framework Convention on Climate Change.

CHINA

Aims at reducing carbon intensity with 60-65% below 2005 levels by 2030. Furthermore, two other goals have been announced: peaking greenhouse gas emissions by around 2030, and increasing non-fossil sources to 20% of total energy by 2030 [5].

CANADA & UNITED STATES

Canada and the US have set CO_2 emissions reduction goals of 30% and 26-28%, respectively, from 2005 levels in 2030 [3,6,7].

INDIA

Has set targets to lower the emissions intensity per GDP by 33% to 35% by 2030 below 2005 levels [3].

RUSSIA

Aims to reduce its emissions of net greenhouse gases by 25% to 30% below the 1990 level by 2030 [3].

INDONESIA

Put forward an unconditional 2030 emissions reduction target of 29% below business-as-usual (BAU) and a conditional 41% reduction below BAU by 2030 - with sufficient international support [8].

BRAZIL

Submitted their INDC with a pledge to keep carbon emissions 37% below 2005 levels by 2025. In addition, it mentioned an *indicative contribution* to reduce emissions by 43% below 2005 levels by 2030 [3].

Figure 1.2 Climate goals and targets of several major countries.

Renewables cost reduction

This growth is largely due to a sharp drop in their levelised cost of electricity (LCOE), as a result of international efforts in research and development. An example are the reductions in unsubsidised wind and solar PV generation costs for the United States (US) depicted in Figure 1.3 [10].

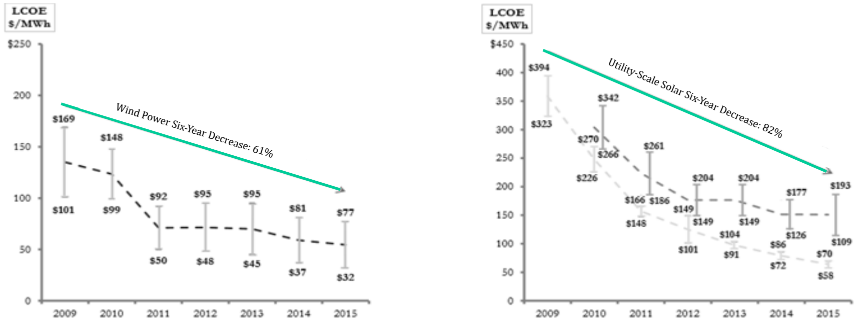


Figure 1.3 Unsubsidised levelised cost of energy for the US [10].

The case of the US is used in the examples in this chapter, since it is the world's largest economy, sufficient data exists, and case-study island Aruba is very much influenced by the United States.

A projection for the estimated levelised cost of electricity for new generation resources in the year 2022 is depicted in Figure 1.4 [12].

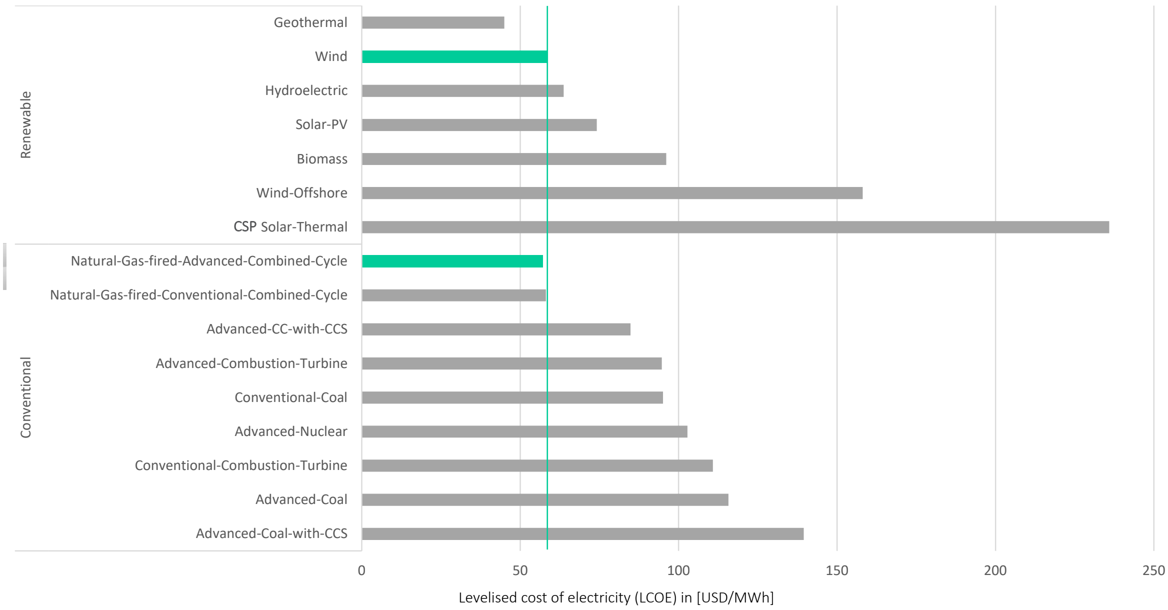


Figure 1.4 Estimated total system levelised cost of electricity for new generation resources in the year 2022 [12].

For the US, it can be seen that in the year 2022, taking into account current developments, that the costs of generation of wind energy will be approximately on par with the most advanced and thus the least-expensive fossil fuel generation technology, i.e. natural gas-fired advanced combined cycle.

Another example is the milestone project has been the 200 MW second phase of the Mohammed Bin Rashid Al Maktoum Solar Park project in Dubai where for the first time in history, the price of generation of electricity from solar PV was lower than that of conventional combined gas-cycle at a record-low tariff of 5.98 USD cents per kWh [11]. Even lower values have been reported since this project achieved financial closure.

Grid integration

From a technical perspective there are challenges that deal with the integration of the electricity from renewables, specifically sources such as wind and solar that have an intermittent nature. The variability and uncertainty of production from these sources makes integration of large shares difficult, since it becomes harder to secure the balance between supply and demand, resulting in a destabilizing effect on the grid [13,14].

In Denmark, a record share of wind energy was integrated into the grid: 42% of electricity supply for the year 2015[2] [15]. However, a challenge is the further increase, which is hampered by operational problems and stress on the existing electricity distribution system [16,17] and the costs related to integration that increase with higher wind penetration levels [18].

The solution is to provide both flexibility and storage. Flexibility in generation, demand and interconnection to other grids. These investments in flexibility can be recommended *"...for any per cent of wind power, especially wind inputs above 20–25 per cent of the demand."* [19]. Storage is used to absorb peaks in renewable energy production and store it for a certain amount of time, ranging from an hourly to a seasonal scale.

Electrifying the transport sector

Apart from eliminating emissions from the generation of electricity, much effort is focussed at reducing the pollution of the transport sector, contributing to 14% of total global greenhouse gas emission in 2010 [20]. The contribution of different economic sectors is displayed in Figure 1.5.

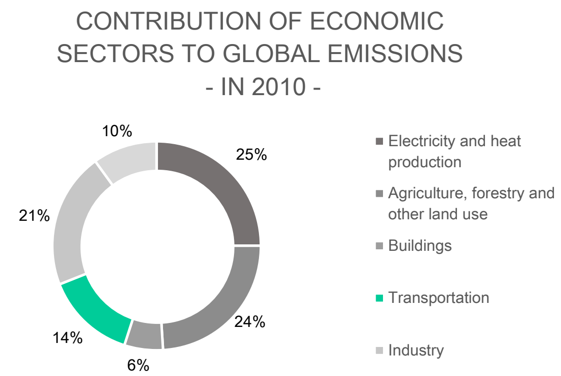
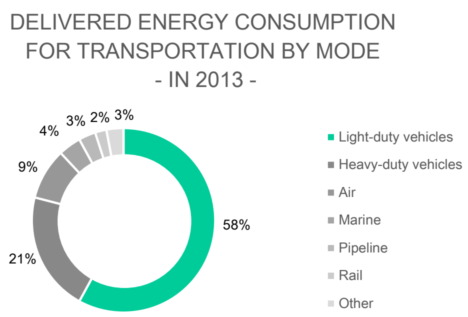


Figure 1.5 Contribution of different economic sectors to global emissions in 2010 [20].

Of the energy consumed by the transport sector in the United States more than half is consumed by light-duty vehicles in 2013. Although this is predicted to decline towards 2040, both relatively and absolutely [21]. Figure 1.6 shows these shares of transportation energy use in the US.



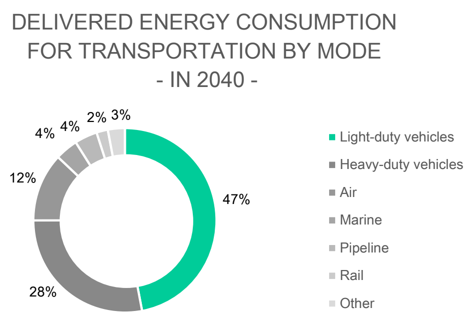


Figure 1.6 Delivered energy consumption for transportation by mode in the US in percentages for 2013 (a) and 2040 (b) [21].

---

[2] One of the main reasons for 2015 being a record year is that was a very windy year compared to 2014, which, from a wind perspective, was a normal year. Conversely, two offshore wind farms, Anholt and Horns Rev 2, were out of operation for one and two months, respectively, due to cable faults. Excluding cable faults, the wind power share would have been approx. 43.5% [15].

In the case of Samsø island in Denmark, the distribution of the energy consumption of transport is given in table 1.1 [22].

Table 1.1 Delivered energy consumption for transportation by mode for Samsø island in Denmark in 2005 [22].

MODE OF TRANSPORTATION	[TJ/YEAR]	[SHARE OF TOTAL]
Ferry traffic	96.2	45%
Private automobiles	65.0	31%
Agriculture	26.4	12%
Trucks/construction	20.9	10%
Buses	3.3	2%

In order to mitigate the impact of transport on climate change, personal transport vehicles are envisioned to be largely replaced by electric vehicles (EVs) during the first half of the 21st century. For example, Norway sets an ambitious target of having 200,000 electric vehicles - 7% of total existing vehicle fleet - by 2018 [23]. In The Netherlands, electric vehicles are estimated to reach a market saturation point at roughly 75% of the market by the year 2040 [24]. In a more recent study [21] these growth trends are endorsed, and although the range of these predictions is quite wide, it is assumed that electric vehicles will grow to such a large market share within this time frame. When combined with clean electricity produced from renewable sources, this can reduce both the entailed CO_2 emissions, as well as the tailpipe emissions of the transport sector.

In the Netherlands, the presence of electric drive vehicles and charging stations has seen a continuous growth trend over the last years. This is likely due to it having the second most ambitious stimulation policy within Europe [25]. However, put in perspective, the amount of electric vehicles (including hybrids) only accounts for less than 1% of the total amount of vehicles.

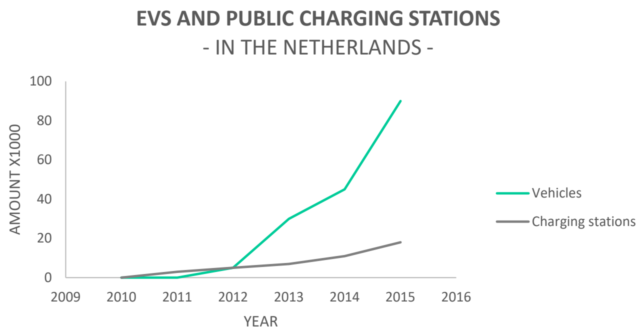


Figure 1.7 Amount of electric vehicles and (semi-) public charging stations in the Netherlands, in numbers x1000 [25].

Electric vehicles and electric drive technology have existed for over a century. One of the first electric cars developed by Ferdinand Porsche in 1898 [26], known as the P1, was effectively a big battery on wheels. Although large in size, the energy content was extremely small due to the primitive battery technology at the time. This resulted in a very limited range of the vehicle. Therefore, although superior in terms of noise, pollution and even motor efficiency, the electric vehicle never took off and lost the 'battle' against the internal combustion car.

Recent developments have led to a sharp increase in battery performance. Nowadays, EVs are powerful in capacity, both in power output and energy content. To give a sense of scale, just a small fraction of the national vehicle fleet of roughly 100,000 EVs together have enough power capacity to meet the electricity demand in the Netherlands, although only for a short amount of time. Or put differently, from an energy perspective, a single electric vehicle is able to meet a household's electricity needs for several days. Moreover, electric vehicles do not require a new fuel supply infrastructure, as they can make use of the existing grid infrastructure, though reinforcements will be needed [33].

Impact of large-scale EV charging

In 2017-2018, five of the large automobile manufacturers will release a competitively priced full-electric vehicle with a 300 km range [27]. It is projected that as a result the market for EVs will take off and will experience significant growth. The impact of charging large amounts of electric vehicles on the grid therefore is and should be a topic of research for utilities. If charging is performed in an unregulated fashion, this will have serious consequences for peak demand, mostly during evening hours. In a study [28] performed for the energy production company of Aruba it is written that already a small amount of electric vehicles – 10% of the total fleet – can have a large effect on the grid. It is stated that if all these vehicles would be charged simultaneously at 4.5 kW, a fairly low number, the increase in peak demand would not be manageable with the current installed generation capacity. It is estimated that roughly 80-85% of charges are done at home and that this will not change significantly in the long run [29,30]. In California, this effect is already perceived since it has the largest cumulative sales of electric vehicles in the US at approximately 52% of national sales [31].

The EV charging impact on the residual demand curve combined with a continued increase in solar power into the generation mix, is called the *Duck Curve* [32]. The concept of residual demand will be explained in section 2.1. This phenomenon is depicted in figure 1.8 for subsequent years of increasing installed capacity of solar power and increasing evening electric vehicle charging. What is visible is a reduction in the residual demand during midday and an increase in peak demand during the early evening hours. This has a severe impact on the use of generating equipment, i.e. power dispatch, through the major decrease in demand during midday and the increase in ramp rate between the afternoon and the early evening. It also means that the amount of reserve capacity during peak hours is significantly decreased, resulting in the need for extra investment in generation capacity. The alternative scenario *2020 with SIS* (in green) depicts the demand profile with solar integrated storage (SIS) for the year 2020, showing the effect of flexibiliy in the form of system-level storage as an answer to both trends.

The development of affordable battery systems and therefore affordable electric vehicles has only just begun and is sparked, not by the car manufacturing giants, but by new companies such as Silicon Valley based Tesla and the Chinese BYD company. What can be observed is a growing availability and uptake of full-electric vehicles (FEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEV). Projections are made for even higher penetrations of EVs in the near future and as new EVs with larger batteries hit the market, this might lead to demand for recharging at faster (Level 2 to Level 3) chargers [33], thereby possibly increasing their peak demand impact on the grid even further.

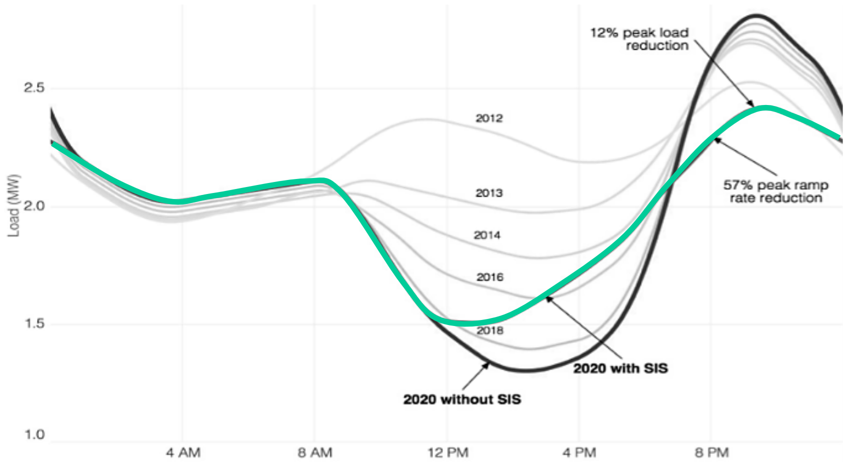


Figure 1.8 The 'Duck Curve' phenomenon, as observed in California's current electricity system, for several historical years and predictions for subsequent years of increasing installed capacity of solar power and increasing evening electric vehicle charging. The alternative scenario *2020 with SIS* (in green) depicts the demand profile with solar integrated storage (SIS) for the year 2020, showing the effect of flexibiliy in the form of system-level storage as an answer to both trends [32].

In terms of alternative technologies, there is a lot of research being done focussed at the development of electric vehicles that use hydrogen as their energy carrier. However, due to low efficiency of the process (producing hydrogen and vice-versa), high investment costs of these vehicles and the fact that a new distribution network needs to be created to facilitate the transport of hydrogen, the real-life implementation of this technology is delayed [34,35].

Combining the best of both worlds

A massive change towards electric-drive vehicles that are all charged at the same time will constitute a major increase in peak electricity demand and therefore a major impact on the electricity grid. The example of the state of California shows that the integration of emission-free technologies solar power and electric vehicles, poses a huge challenge for grid management. However, shifting the loads of electric vehicles in a way that is beneficial for the system and corresponds to production of renewable energy sources has the potential to solve both problems. The Rocky Mountain Institute has shown the impact of optimised charging for five different states in the US [33] and conclude that *"…controlled charging can help optimize the use of grid resources, avoid having to invest in new peak generation capacity, and even integrate more wind and solar."* This has led to the following question:

What if we could tap in to the potential of these 'big batteries on wheels'?

If this move to zero-pollution vehicles is accompanied by a transition to a system with high penetration of renewable energy sources, serious reductions in CO_2 emissions are within reach. Since these EVs are purchased for the function of transport and therefore have a large power and energy capacity, but are idle 96% of the time [36], there exist clear advantages of *"…intelligently connecting the vehicle and electric power system, using the vast untapped storage of an emerging electric-drive vehicle fleet to serve the electric grid." [37].*

EVs are able to offer the flexibility in demand and (distributed) storage attributes that are required for a system with a large share of intermittent renewable energy sources. This will lead to a reconceptualization of the entire energy system.

"The prospect of V2G is to carry us along both these paths together, more quickly and economically than has been thought possible when planning either system in isolation." [38].

This synergy is especially appealing in small isolated (and thus vulnerable) power systems since integration of renewables is more difficult there than in larger systems. Due to the smaller size, the impact of one electrical load is larger and since there is no exchange possible with other grids, more back-up power is required.

Large-scale demonstration of smart-grid applications, such as vehicle-to-grid technology are needed to prove the concept, ensure public acceptance and to involve and bring together the different parties that aim to develop and implement these innovations. Preferably this should be a joint project between research institutes, companies and led by a public party, e.g. local island government. As crucially indicated by Jorgensen [22], *"Public institutions should be involved as the first to invest in electric vehicles. Without a locomotive, it will be hard to achieve momentum."*

Islands as example to the world

Islands are considered first-movers for the transition to a sustainable energy supply. Their dependency on the import of fossil fuels, and thus high electricity generation costs, combined with mostly abundant renewable energy resources makes a strong case for the introduction of renewable energy sources. In many cases rising sea levels directly affect the lives of islanders and thus island governments have become strong advocates for a reduction of global CO_2 emissions. Other arguments are to reduce dependency on foreign import of energy carriers, to change from centralised, monopolistic electricity generation towards a more decentralised, distributed production and since the cost of producing electricity on the island is high, there is a good business case for renewable energy sources (RES). Therefore, transitioning provides positive impact from a political, social and economic perspective.

Several small islands or archipelagos have ambitions to become a 100% renewable energy island: Samsø island in Denmark, El Hierro (part of the Canary Islands), the Azores archipelago, Jeju island in Korea, Aruba in the Caribbean and so forth. Many are well underway at achieving this goal by already having higher shares of renewable energy than most countries. However, the share of renewable energy of the primary energy still remains low. For a large part this is caused by the energy use of fossil fuels for agriculture, transport, and industrial activities. These isolated communities provide opportunities for research and industry as Living Labs to test and showcase innovative solutions in the field of renewable energy but also within the broader context of smart (micro) grids, system integration, decentralised energy production, sustainable transport, clean water production and waste management. Island communities feel a strong need to transition towards a more sustainable energy supply and thus, storage and flexibility are key enablers for this transition [39].

Managing the transition

This change brings about another change in the interaction between the actors involved in both generation and demand of electricity. *"Both increased decentralised production and the use of wind power will result in a growing number of small and medium size producers, who will be connected to energy networks and in particular to electricity grids, which are originally designed for monopolistic markets. Therefore, many new problems will arise, in relation to management and operation of energy transfer as well as in relation to efficient distribution of wind power and other renewable energy sources in the grids." [40].*

In order for large-scale adoption to take place, several conditions have to be met that foster innovation [41]:

- the presence of entrepreneurial activity is essential,
- research needs to be carried out to create knowledge,
- plans and research objectives need to be aligned,
- a market needs to be formed,
- investments are needed in development and implementation of the technology,
- knowledge needs to spread through the different industry sectors, layers of society and to the different corners of the world, and
- the innovation needs to overcome the resistance of change by parties that have vested interests, and therefore an interest in keeping the status-quo unchanged.

To shape this transition and guide the changes in the right direction, management and nurturing of the innovation processes is required. This requires leadership and vision, but above all collaboration.

Islands are a special case when it comes to innovation. An innovation has to grow from a niche into a socio-technical regime and ultimately nest itself into the overarching landscape, as defined in the multi-level perspective framework [42]. However, in the case of islands, the differences between these levels are less stark. This makes that a large-scale adoption of a technology into the regime and ultimately into the landscape can happen a lot faster in a mini-society such as an island.

Aruba as case study

A connection is made to the developments and initiatives pushing forward sustainable energy on the formally called Caribbean part of the Kingdom of The Netherlands. This includes the countries Aruba, Curacao and St. Maarten, and the special municipalities Bonaire, Saba and St. Eustatius.

These islands are working hard on setting and achieving their goals with regard to moving towards a sustainable energy supply [43]. Aruba wishes to be a testing ground for innovative sustainable solutions [44] and a stepping stone for the Dutch business sector to the Caribbean and South America [45]. The choice has been made to focus on Aruba as case study within this thesis. This choice will be explained in more detail in chapter 4.

Relevance

This study will provide entrepreneurs, researchers and (advisors of) island governments with useful insights that cover the technological benefits of the investigated scenarios, but also deals with the economic elements of the transition to a more sustainable energy and transport system. The results can be used for further analysis to determine a strategy for the smart integration of electric vehicles into an island power system.

1.2 Research objective

This thesis entails the modelling of the transition to a state of high-penetration of renewable energy sources specifically within an islanded energy supply, enabled by means of the smart integration of a large fraction of electric vehicles.

The first aim is to investigate how the synergy in the development of a large fleet of EVs and new installed solar and wind energy generation capacity, through flexible intelligent charging and distributed storage of energy in the EVs' batteries, is affected by the implementation of different control scenarios and different charging infrastructure types. The results will be expressed in terms of the effect on conventional fossil-fuel electricity generation (residual power demand), the amount of curtailed renewable energy and greenhouse gas (CO_2-eq) emissions for both the small island power and transportation system.

The second aim is to compare the technical performance of the system to the economic potential, by evaluating the cost of implementation of the investigated infrastructure and control options, the power generation levelised cost and the total system levelised cost.

These objectives have led to the following research questions:

Main research question

How can flexible demand and storage of electrical energy through the controlled charging and discharging of a large fleet of EVs, increase the utilisation of renewable energy in the energy mix of a small islands?

Sub-research questions

1. How do technical gains that electric vehicles can provide in a future island power system with a high penetration of renewables depend on different control scenarios,
    a. uncontrolled vs. controlled
    b. one-directional (G4V) vs. bi-directional power exchange (V2G)

    and different implemented charging infrastructure?

    a. only home charging vs. public&home charging
    b. low power (1.5 & 7 kW) vs. high power (7 & 21 kW)

2. What is the relation between the benefits and the required investments in infrastructure and cost of implementation of these scenarios?
    - What are the charging infrastructure and control costs?
    - What is the value of the effects on the power system?
    - Is there an economic incentive to install this infrastructure and control options?

These impacts are measured by the effect on the following key technical indicators:

- residual power demand
- curtailed renewable energy
- and CO_2-eq emissions?

and key economic indicators:

- charging infrastructure and control costs
- power generation levelised cost (sLCOE)
- system levelised cost (sLC)

1.3 Outline

The outline of this thesis can be understood as moving from a general analysis of islands and their transition towards a sustainable energy system towards an island-specific case study. In the process, a database is made of islands in the predefined population range (10,000-1,000,000). This incorporates general data on population, land area and highest elevation, but in the future will include more specific data on energy consumption, if there is a grid connection to the mainland and what targets are set for renewable energy implementation.

This study is divided over multiple chapters, this is explained in the following paragraphs:

2. Background

Chapter 2 will give an overview of background knowledge and concepts related to future power systems, smart charging and vehicle-to-grid technology, ancillary services and grid reserves.

3. Literature review

Chapter 3 will review existing literature on transition of small islands to a sustainable power system in combination with the integration of EVs. Furthermore, it will discuss the positioning and contribution of this thesis.

4. Case study

Chapter 4 will elaborate on the current situation of the energy and transport system on Aruba and the parties involved in the integration of renewables and electric vehicles. Detailed information regarding local conditions that has been gathered through interviews with stakeholders and organisations on the island is summarised here.

5. Model

Chapter 5 will deal with the assumptions, structure and functioning of the model, made in MATLAB. This model represents the small island power system of Aruba that incorporates elements such as conventional energy generation in the form of steam turbines and reciprocating engines, and renewable energy sources in the form of wind turbines and solar power plants. Moreover, it includes individually modelled electric vehicles that have unique driving cycles and are charged based on a chosen optimisation strategy.

6. Optimisation

Chapter 6 will discuss the choice for the optimisation approach used in this thesis and the implementation of the dynamic programming to the case of controlled electric vehicle charging.

7. Results & Discussion

In chapter 7, the results generated for the case of Aruba in the form of the influence of controlled electric vehicle charging on the residual demand, power generation dispatch, curtailed energy and emissions will be presented and discussed. An economic analysis shows the feasibility of investigated scenarios.

8. Reflection

In chapter 8, the results will be compared to the main findings discussed in the literature review, and a reflection will be made on the structure, functioning and assumptions made in the model.

9. Conclusion & Recommendations

Chapter 9 will deal with final conclusions based on the presented results. Recommendations for future research will be given based on insights gathered in this thesis.


ARUBA

2. BACKGROUND

2. BACKGROUND

This chapter is dedicated to explain the main concepts that play a role in this thesis. The aim is to provide the necessary information that is needed to understand the analysis and reasoning throughout the rest of this thesis.

2.1 Energy system analysis

Load duration curve

To understand how the electricity consumption of a load varies throughout the year, a load duration curve can be made by sorting the energy use per time period from high to low [48]. It plots the load power [GW] against the part of the part of the year [hours]. From this graph it can be found for how many hours in the year the load power exceeded a certain value. This is depicted in Figure 2.1.

This means that the information in this graph is not time-specific anymore. For an in-depth analysis of the load pattern throughout the year or throughout the day, the original time series needs to be analysed.

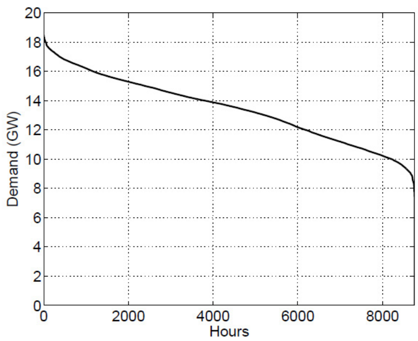


Figure 2.1 Load duration curve [49].

Residual demand

The concept of residual demand or residual load and its depiction in a residual load profile is very important in the analysis of energy systems with high penetration levels of renewable energy. In principle it is created by subtracting the available renewable power from the demand. A surplus of renewable energy is thus represented by a negative residual demand, which means that if no storage is implemented, this is spilled renewable energy.

2.2 Island power systems

Island power systems are uniquely designed to suit the energy needs of the island. System characteristics such as size and type of generators will depend on weather, population and economic activity. Therefore, within an island archipelago, you will find that the islands have isolated, differently-sized and most importantly, one-of-a-kind systems. Being mostly small in size and isolated from other grids, island power systems are less able to respond to shocks. A voltage drop has a larger impact on the system and a balance between supply and demand is harder to achieve. Connection to the mainland through an underwater transmission cable can be established, but the cost rises sharply with distance and depths that have to be crossed [46]. This results in the island power system requiring more reserves.

Since the installation of say a 30 MW wind energy plant will have a larger impact on the share of renewable, and thus intermittent, energy sources within the grid, islands will be among the first to experience the problems related to large deployment of renewable power. This includes operational problems in the form of stress on grid components, such as transformers, cabling and converters. For example, for the island of Reunion, it has been calculated that for the current system a maximum penetration level of energy from intermittent sources such as wind and solar of 30% is allowed [47].

Furthermore, a very important notion in the case of islands has to be made regarding energy production variability. In continental power systems, a geographical spread in generation from for example wind turbines decreases the overall variability of this energy source to a large extent. Whereas in the case of geographically small power systems, such as islands, the aggregate power of wind turbines that are installed in close proximity of one another will have a higher overall variability.

2.3 Smart charging and V2G

The solution put forward in this thesis is to create a large increase in flexibility through smart charging and distributed energy storage through vehicle-to-grid technology. These concepts form the core of this thesis and the following section is devoted to explain them in more detail.

Demand response

Demand side management (DSM) or demand response is a smart grid service which aims to change the electricity consumption pattern. This is envisioned as a way to provide flexibility in the future power system and is considered to have a high technical potential in system with a large share of renewable energy. Although very beneficial from a theoretical point of view, implementation of demand response requires not only an ICT or communication infrastructure, but also an impactful behavioural change. These systems are currently tested in smart streets or living labs in e.g. the Netherlands, where users are incentivised to switch on their appliances at a later moment through a price signal, or where smart appliances are used that are able to make this decision on their own through cost optimisation, based on the constraints given by the user and (forecasts of) energy prices. It therefore asks for thorough review and consideration of how this can actually be implemented in a real-life setting.

Smart charging

Demand response can be implemented in the form of smart charging of EVs by shifting their demand away from positive peaks in the residual demand and by absorbing as much of this surplus of renewable energy as possible by drawing power from the grid.

EV charging can be coordinated and controlled by an aggregator. This can be done with help of information communication technology and based on the specific needs of the EV, its user and the used charging station. This allows for control of the power flow to the vehicles in both the time domain as well as the magnitude of the power flow. This is therefore called smart charging, or by others referred to as intelligent or dynamic charging. The more general term when electric vehicles are connected to the grid and are in the position to aid in balancing through demand response, is grid-for-vehicle (G4V). Smart charging will be needed to prevent traditional grid reinforcements [33]. These will be the results of large peaks of demand due to the immediate charging of electric vehicles at arrival home after working hours.

"For a typical EV and driving behaviour, an EV owner needs to re-charge his car every four days. This flexibility can play a crucial role in power systems with large RES penetration, since it could replace the flexibility that is normally provided by conventional generation units but that most RES are only able to provide to a limited extent." [49].

This explains the concept of the major paradigm shift within the energy sector: electricity demand for EVs will become a response to the availability of power from renewables.

Vehicle-to-grid technology

Expanding this idea leads to not only drawing power from the grid, but also supplying it back when this is beneficial. This is aptly named vehicle-to-grid (V2G) technology and is a form of storage of electrical energy. With V2G technology it is possible to not only shift EV charging demand away from peaks in the residual demand and reduce peaks as a result of uncontrolled charging, but also supply power back to the grid to remove these peaks and flatten the residual demand curve. Naturally, this can only be done provided that the EVs are connected to the grid and are cleared by their owners to be used in grid balancing.

A definition for a vehicle-to-grid service is given by Andersen [50]: *"The act of influencing the timing, rate and direction of the power and energy exchanged between the EV battery and the grid to yield benefits for user, system and society."*

Pioneering work has been done by Kempton, Tomic and Letendre [51,52] in which the potential of vehicle-to-grid technology is evaluated through a quantitative analysis to better understand the impact and benefits of connecting electric vehicles to the electrical power grid.

"Over just a decade or two, V2G could revolutionize the ancillary services market, improve grid stability and reliability, and support increased generation from intermittent renewables." [51].

Three markets are identified in [52] as 1) peak power market, 2) spinning reserves market and 3) frequency regulating market. These are depicted in Figure 2.2 [53].

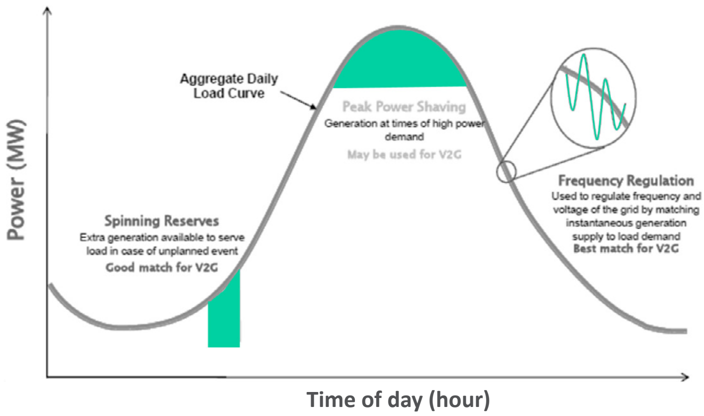


Figure 2.2 Vehicle-to-grid (V2G) functions [53]

The peak power market is found not to be competitive for large continental power systems, but ancillary services such as spinning reserves and frequency regulating could be profitable for the EV user [52].

"We suggest that in the short-term, electric-drive vehicles should be tapped for high-value, time critical services - regulation and spinning reserves - which can be served by about 3% of the fleet. As those markets are saturated, V2G can begin to serve markets for peak power and storage for renewable electric generation." [38].

Within an island setting, this case will be different and since there mostly do not exist any electricity markets on islands, the integration of EVs may prove to be much more valuable. In Europe it is currently prohibited by law to supply energy from a battery into the national grid [54]. This means that within the current legal framework the implementation of vehicle-to-grid technology on a national scale is not possible. However, this topic is under debate and policy makers are discussing a possible change of this framework.

"The long-term case for V2G boils down to making a decision to keep the electric system and vehicle fleet separate, in which case we substantially increase the cost of renewable energy because we have to build storage to match intermittent capacity, or whether we can connect the vehicle and electric power systems intelligently, using the vast untapped storage of an emerging electric-drive vehicle fleet to serve the electric grid." [38].

There are pilot projects showcasing the potential of V2G, such as in the city of Utrecht where an electric vehicle receives power from a micro grid that connects several PV systems and one building. Another example case is implemented by the US military [55]. And according to Nissan [56] in roughly 6 months, cars will be on sale that will have V2G capabilities, i.e. electric vehicles that will have a bi-directional inverter on board.

Other than connecting to the grid, there are many possibilities for interaction and exchange of power with other power systems, such as buildings, offices, homes, other vehicles, etc. That is why the umbrella term for connecting them is formulated as vehicle-to-X (V2X).

However, the true potential for vehicle-to-grid technology and its adoption depend on the economics and if the business case is sound. Users will need to be incentivised to let their vehicle participate in these programmes. Tesla's CTO is not convinced that this will become a reality in the near future [57]. The reason is that is voids the battery warrenty due to the negative impact on battery lifetime as a result of extra cycling. On the other hand, a study [53] performed by the US Department of Defence shows that V2G peak shaving activities add 30% extra cycles comparable to normal driving use, but the value of this service provided to the grid operator is estimated at 150 USD per month. Thus it is debatable whether in the near future this service will be provided by EVs. However, radical changes are expected to occur to the power system, which can make the case for V2G more appealing. These are discussed in the next section.

Future power system

The current power system with a residual demand curve that very strongly resembles the demand curve – thus a repetitious pattern with gentle and predictable peaks – will be very different in nature from a future power system that is highly reliant on intermittent renewable energy sources with a much more inconsistent and ever-changing pattern. This transition and therefore change of the demand pattern is depicted in figure 2.3.

Figure 2.3 Overview of changes in the power system depicting a residual load pattern for two days, showing the impact of the transition from a predictable, cyclical pattern to a more inconsistent and ever-changing pattern of an energy system with many renewables and a dynamic market with many players.

Within future power systems the role of loads, storage and thus also electric vehicles will inevitably change. EVs will participate in peak shaving through demand response programmes and will be able to supply services to the grid, for example to provide added grid stability through frequency regulating. These services are often referred to as *ancillary services*.

These ancillary services include i.a. balancing and stabilizing of the grid. EVs can therefore (partly) take over the role of conventional grid components and reserves. Since understanding of the different types of services and reserves within power systems and their nomenclature is of importance to understand the rest of this thesis, the following section is dedicated to the explanation of these concepts.

2.4 Ancillary services

Future battery services

A recent study [58] illustrates the future role of batteries within the power system. The authors identify a total of thirteen services that can be provided by battery systems to three different stakeholders: *System operators, Utilities and Customers*. These include the vehicle-to-grid functions as stated in section 2.3 as the first three items: *Energy Arbitrage, Frequency Regulation* and *Spinning/Non-Spinning Reserves* (here the term energy arbitrage is introduced instead of the term *Peak Shaving* to describe the purchase and subsequent sale of electricity to reduce peaks in the load curve). In addition, another ten different services are identified. These other services or functions include e.g. *Voltage Support* which deals with maintaining voltage on the transmission and distribution system within an acceptable range to ensure that both real and reactive power production are matched with demand. This last function can also be performed by EVs and can thus be added to the original list of V2G functions. An overview of these services is given in table 2.1.

Table 2.1 Overview of ancillary services [58]

SYSTEM OPERATOR SERVICES	UTILITY SERVICES	CUSTOMER SERVICES
1. Energy Arbitrage	6. Resource Adequacy	10. Time-of-Use Bill Management
2. Frequency Regulation	7. Distribution Deferral	11. Increased PV Self-Consumption
3. Spinning/Non-Spinning Reserves	8. Transmission Congestion Relief	12. Demand Charge Reduction
4. Voltage Support	9. Transmission Deferral	13. Backup Power
5. Black Start		

The study makes an analysis of the value that each function represents to the stakeholder and gives a detailed proposition of how batteries can perform this function. However, within the current regulatory framework, many of these services cannot yet be fulfilled by battery systems. Due to restrictions they are trapped behind the meter. Figure 2.4 displays these functions once more and also shows at which level these functions can be performed: *Transmission, Distribution,* and *Behind the meter*.

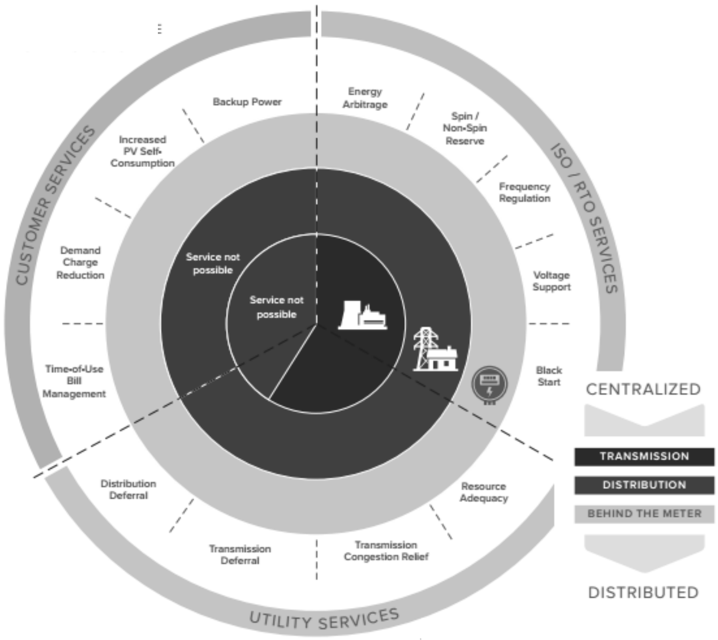


Figure 2.4 Overview of battery services [58]

Grid reserves

Operational reserves or grid reserves can be initially split into two types: *Non-event Reserves* and *Event Reserves*. The former deals with normal continuous operation and the latter with infrequent events. These categories and their subdivision into different types of grid reserves is the topic of this section. An overview of these operating reserves is given in figure 2.5.

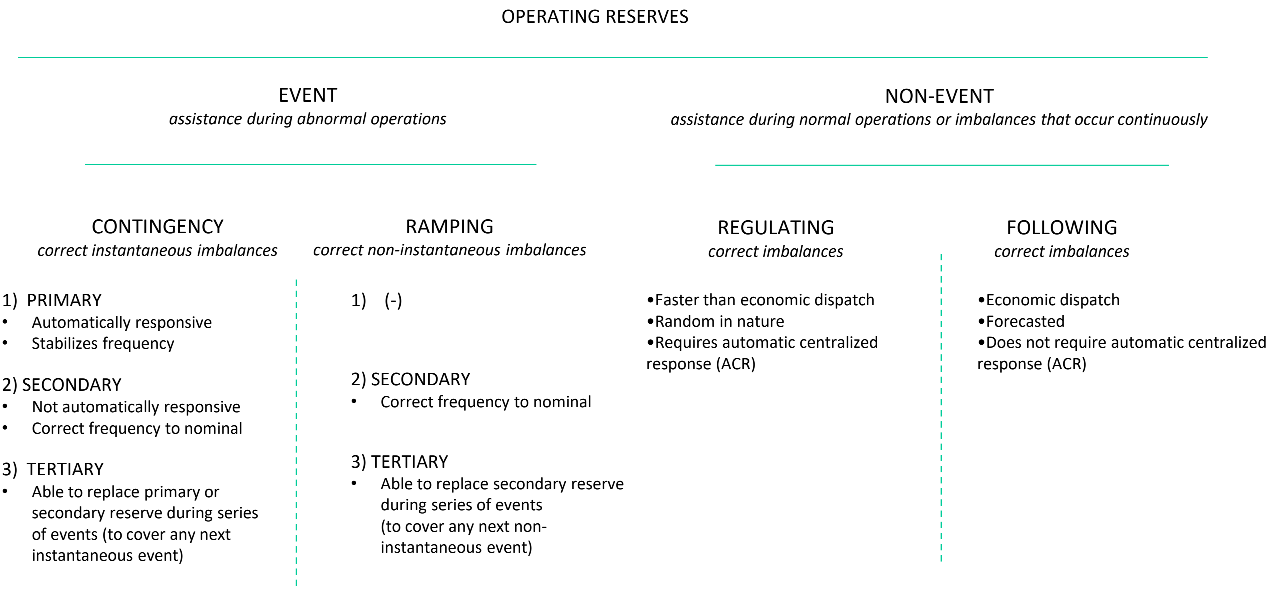


Figure 2.5 Overview of operating reserves

Non-event reserves

Non-event reserves can be classified into two categories: *regulating* and *following reserves*. Regulating reserves deal with fast and frequent imbalances that occur randomly. Because of their random nature, these happen faster than economic dispatch optimisation and are therefore controlled by automatic centralised response (ACR) or automatic generation control (AGC). This means that the regulating reserves need to correct the imbalance before the dispatch cycle is finished. Depending on the system operator characteristics, this may be up to an hour and or as short as five minutes.

"In many isolated systems, this reserve is provided by governor response (e.g., U.K. and Ireland, other larger island systems). The resources with governors can then cover the normal balancing needs inside the economic dispatch interval automatically." [59].

Following reserves deal with correcting imbalances predicted to occur in the future and are therefore governed by economic dispatch optimisation. These imbalances are less random, but larger in magnitude. These reserves are used to follow the typical load pattern.

Event reserves

Event reserves on the other hand are to cover infrequent and sudden imbalances. These reserves are divided over two categories: instantaneous imbalances are covered by contingency reserves and non-instantaneous imbalances are covered by ramping reserves.

Instantaneous imbalances include *"...a large loss of supply either from generating resources or large transmission lines carrying imports, but more generally can consider loss of large blocks of load as well." [59].* This form of inbalance happens on a timescale of minutes. Non-instantaneous imbalances, on the other hand, are caused by events such as an unpredicted drop in production from wind power. These happen on a much slower timescale, i.e. a drop in wind power production over the course of several hours, leading to an increase in production requirement from conventional generation.

Within these two categories, there exist three sublevels of primary, secondary and tertiary reserves. An overview of these reserves is given in table 2.2.

Table 2.2 Overview of primary, secondary and tertiary services.

Reserve	Type	Description
Primary	Contingency *= frequency response or regulating reserve*	Primary contingency reserves are to stabilize the grid frequency by means of the generators inertial response and governor control.
Secondary	Contingency and ramping *= frequency regulation or restoration reserve*	Secondary contingency or ramping reserves are to restore the grid frequency, i.e. bring it back to its nominal value.
Tertiary	Contingency and ramping *= supplemental or replacement reserve*	Tertiary contingency or ramping reserves are used as back-up to fulfil either the role of the primary or secondary contingency reserve in the occasion that one of these would fail or if an additional event were to occur shortly after the first event. Therefore, they need not be as fast as the reserves they are replacing.

Note: Primary ramping reserves do not exist since the ramping reserves are used to cover for imbalances that occur over a longer period in time, and thus there is no fast frequency stabilization needed such as with the contingency events.

Other names are also used for these reserves. Primary reserves are referred to as *frequency response reserves.* Secondary reserves *as frequency regulation reserves* - these can be *spinning or non-spinning reserves*. And lastly, tertiary reserves are also called *supplemental reserves.*

> Caution needs to be placed by the name frequency regulation reserves, which in writing is very similar to frequency regulating reserves. However, in meaning both are distinctly different. The difference is in the magnitude of the frequency drop or change.
>
> Frequency regulation deals with restoration of the frequency to its original value after an event (large fluctuations), whereas frequency regulating deals with keeping the frequency within its specified bandwidth during non-event situations (small fluctuations). The first is performed by spinning or non-spinning reserves, the second through governor response on synchronous machines.

Spinning reserves are defined as generators that are running at the grid frequency and are thus synchronised and ready to serve any extra demand. Non-spinning reserves are fast-start engines that are idle, but can be started up and be able to supply load within minutes. These reserve functions can also be performed by a load that can instantly or after a specified time be disconnected [59]. For the case of islands the following is stated about spinning reserves in [60]: *"These [spinning reserves] are mostly diesel generators and must be constantly connected to the system."*

Reserves and the integration of renewables

Event reserves

In larger power systems, a fault in an individual wind turbine (or PV cells) is considered negligible and therefore not a contingency but an imbalance that can be regulated using the non-event regulating reserves. However, in smaller power systems such as those for islands, this may not be the case and should thus be covered by the event reserves.

The normal variability and uncertainty of renewable energy production is not considered a contingency, since it is possible to create accurate forecasts of e.g. wind speeds in a certain area. The correction of non-instantaneous imbalances due to unpredicted loss of production should be covered by ramping reserves. Thus an increase in installed capacity of variable generation will result in an increase in ramping reserves. Since these ramps are mostly large and rare, these reserves need not be as fast or can even be offline.

Contingency reserves, on the other hand, can also be used to correct for drops in renewable power production, but the extent to which this can be done is dissuaded: *"If [all secondary] contingency reserves were used to compensate for the drop in wind, there would be no more capacity available to respond if a conventional contingency were to occur during these hours and the system might have to shed load." [59].*

Recently installed variable generation sources such as wind turbines and large-scale solar parks lack the characteristics of inertial response and governor control that conventional synchronous generators possess. This means that having displaced these conventional power sources by renewables has also decreased the primary reserves that are responsible for stabilizing the frequency in a contingency event. However, newly designed wind turbines are able to emulate this form of control response [61,62].

Non-event reserves

The regulating reserve and following reserve are – depending on the time-scale – directly affected by the variability and uncertainty of renewable power generation. Regulating reserves have to cover for any short-term forecast errors. On a longer time-scale, following reserves have to account for the errors in for example the day-ahead forecasted fluctuations in magnitude of variable generation. Therefore, accurate forecasts are needed to prevent increases in non-event reserves.

Advanced scheduling through high-resolution unit commitment can help to cope with small-scale uncertainty and variability, thus reducing regulating and following reserves. However, high penetrations of variable generation sources result in an increased large-scale uncertainty of production and makes the net load less predictable. Consequently, this results in the need for more following reserves with a higher ramping rate.

Loads as reserve

Other than correcting an imbalance by changing the amount of supplied energy, it is also possible to change the demand for power. This can be done by a responsive load. There is an added advantage to this, the action can occur a lot faster than an increase in generation power, since there is negligible ramping for the disconnection of a load. Nowadays, storage devices such as battery systems and flywheels are entering the reserve market by supplying short-term balancing services, e.g. regulating reserve [59].

3. LITERATURE REVIEW

3. LITERATURE REVIEW

3.1 Thesis topic

As explained in the Introduction chapter, the topic of this thesis is the modelling of the transition to a state of high-penetration of renewable energy sources specifically within an islanded energy supply, enabled by means of the smart integration of a large fraction of EVs. This chapter explains the literary setting of this topic and is structured as follows. The first section will discuss the fields of research that are combined in this thesis and the recent developments that have been made, the second section will go into the papers that are identified as core papers and the third and last section will deal with the positioning of this thesis.

The topic of this research can be characterised as a combination of three different fields of research. These are:

A) Smart charging and integration of electric vehicles
B) Distributed storage and demand response in future power systems
C) Integration of high-shares of RES in isolated micro grids / islands

Naturally, more connections can be made to different fields of research, but these are considered as the main themes. These themes have been the focus of research for quite some years, however the combination of all is a very new subject. This is shown by the amount of articles that exist within this domain. Namely, within this combined region of research fields – specifically carried out for islands – there exist only 15 articles and 26 conference papers[3]. However, when the search query is extended to include also results that are focussed on micro grid systems, a total of 63 articles and 106 conference papers is found. Still, considering the full body of literature this is rather limited, as searches for either one of the individual fields yield multiple thousands of articles. It has to be noted that most of these articles and papers touch upon the possibility and the potential of using EVs as responsive loads or distributed storage, but do not go into much detail.

A short descriptive paragraph is devoted to each of these themes to explain in more detail what they entail and what developments have been made in research within that field. References are made to research papers not with the aim to give a complete picture, but to illustrate the types of research that have been carried out up to the time of writing.

Smart charging and integration of electric vehicles

The large-scale adoption of electric vehicles has long been predicted [21,24,25]. Therefore many researchers have worked on topics such as to develop the technology needed for electric cars and the charging infrastructure, e.g. connectors, cabling, converters, ICT systems etc. Others have investigated the impacts of EV charging strategies on the electricity distribution grid [49,64,65], designed business models for stakeholders in electric mobility such as aggregators that provide collective EV charging [66,67]. Other studies have been carried out that evaluate public acceptance and willingness to pay for EVs and their attributes [68,69] with the aim to develop effective policies to accelerate the uptake of EVs and the implementation of charging infrastructure [70].

Pioneering studies have been [71,72] that have looked deeper into how electric vehicles can allow for a higher share of renewables in the grid by controlled charging and feeding power back into the grid in relation to the market value of these forms of power and the expected revenues and costs. This form of controlled charging and feeding electricity back into the grid makes the EV act as a responsive load and distributed storage unit. This has been discussed in more detail in section 2.3. Another important study has been carried out that investigates integration of V2G technology into a model at national scale which includes electricity, transport and heat and hourly variations in supply and demand [73]. It shows that this allows for much higher levels of integration of wind energy and great reductions in CO_2 emissions.

[3] A search in Scopus carried out on 24/4/2016 yielded a total of 15 articles and 26 conference papers when the following search query is used: ((TITLE-ABS-KEY((“Electric vehicle” OR EV OR PHEV OR “Electric transportation”) AND (“smart grid” OR “demand response” OR “load management” OR (responsive AND (load OR demand)) OR “distributed storage” OR V2G OR “vehicle-to-grid”) AND (“small island” OR island) AND ((“Renewable energy” OR wind OR solar OR “stochastic generation”) OR ((power OR electricity OR distribution) AND (grid OR system OR network)))))

Distributed storage and demand response in future power systems

A very important aspect for future power systems with high shares of renewable energy is increased flexibility. Therefore, a lot of work has been done on the potential of different energy storage technologies of energy [74], both on short-term, second to hour scale and on long-term, day to month scale. This includes storage in flywheels, electrical batteries, pumped hydro and chemical storage such as power-to-gas or synthesised hydrocarbons fuels. Apart from the timeframe of storage also their scale and the level of centralization is changing and therefore the subject of much research. Since renewable energy generation is much more distributed as opposed to conventional centralised generation, storage will also become more decentralised and smaller in size. Examples are the development of community-scale stationary batteries that allow for storage of locally produced electricity, and hydrogen storage facilities that convert surplus wind power into long-term energy storage in the form of hydrogen gas [75].

Another way to allow for a match in supply and demand of energy, is shifting the demand to times that the energy is available from variable energy sources such as wind and solar. It is a smart grid service which ensures that electricity is consumed when it is produced, and not the other way around. This is called demand response or demand side management, and it can be done for any type of electrical load. The load can be remotely controlled by the grid operator or a third party. Another option is that the consumer is triggered to delay switching on the appliance or starting up the manufacturing process through price signals, where high prices indicate constraints in the network and low prices indicate excess energy. Many studies have been done within this field that focus on strategies for the penetration of renewable electricity [76], how market design could be adapted to the growing demand for flexibility [77], or on congestion management for the distribution grid [78].

Integration of high-shares of RES in isolated micro grids / islands

Micro-grids are a popular topic of research as they allow for testing and showcasing of a certain technology at a small scale. Islands are a prime example of small or micro-grids and therefore integration of renewable energy sources into micro-grids is also studied in this thesis.

The introduction of renewable energy sources within the existing power system infrastructure has serious consequences, certainly on isolated systems such as islands. Many case-studies have been performed for islands to evaluate the potential and impacts of large-scale integration of renewable power for islands [79-86].

Furthermore, numerous analyses have been done to investigate the impacts of high shares of renewable energy on grid stability [13,14], control strategies [87,88,89] and optimisation tools [90,91], energy markets [92], policy structures and socio-economical development [93,94]. Others have focused at integration of for example wind power with pumped hydro storage [95,96,97].

3.2 Core papers

In this section, several of the papers will be discussed that are situated within the core of the research topic. An overview of these papers is given in Table 3.1.

Table 3.1 Overview of core papers

1st Author	Year	Title	Citation
Diaz	2015	Impact of Electric Vehicles as Distributed Energy Storage in Isolated Systems; The Case of Tenerife	[60]
Pina	2014	Energy reduction potential from the shift to electric vehicles; The Flores island case study	[98]
Camus	2012	The electric vehicles as a mean to reduce CO2 emissions and energy costs in isolated regions. The Sao Miguel (Azores) case study	[100]
Kadurek	2009	Electric Vehicles and their Impact to the Electric Grid in Isolated Systems (São Miguel, Azores)	[35]
Denny	2013	A Smart Integrated Network for an offshore island (Aran islands, Ireland)	[101]
Ilic	2013	The Tale of Two Low-Cost Green Azores Islands [Engineering IT-Enabled Sustainable Electricity Services]	[102]

The research approach of each paper will be shortly discussed and interesting insights from the analysis and possible follow-up tracks for further research will be highlighted.

--

Diaz et al. [60] have looked into the impact of electric vehicles as distributed energy storage in isolated systems. An analysis is performed on the island of Tenerife, belonging to the Canary Islands archipelago. The paper has aimed to be of great use for the design of the island's energy policy. The attempt has been to measure impact of two aspects on the power system: a larger installed capacity of renewables and the introduction of EVs as distributed energy storage system.

The improvement indicators used in this research are:

- Renewable share [%] = total renewable energy divided by the total energy consumed
- Energy spilled [%] = total renewable energy that could not be injected into the system divided over total renewable energy available
- CO_2 emissions [$kgCO_2/kWh$] = summed emission rates per technology during year for each kWh generated
- Levelised cost of generating electricity [€/MWh] = weighted sum of LCOE of each technology on basis of share of total energy consumed
- Oil internal market (fuel dependence) [%] = total TOE reduction (through EV usage ánd renewable electricity production) divided by the total oil imports from internal market

Two types of scenarios are analysed: G4V and V2G. For each case two different EV fleet sizes have been analyzed. In the case of G4V, fleets will be managed by an aggregator that allows over-night charging in order to increase the off-peak of the system and flatten the total demand curve. In the case of V2G, over-night charging is implemented, plus injection of energy into the grid in peak hours. This can thus both serve as backup for intermittency of renewables and to decrease load spikes during peak hours.

In the model the researchers have characterised the instant operation of alternative (read renewable) power technologies during a particular period of time. No optimisation is done. The EVs supply power when a drop in renewable production is over a certain reference value or when total demand is over a certain limit value. The EVs are modelled as a group, not individually. Power to and from EVs is based on 7 kW for home and 22 kW for work. Charging at home is done overnight but the time of availability is not given. Charging at work is only possible for 5-6% of vehicles.

Interesting to note is that the TSO requirement is an absolute minimum of instant power at each moment of time of 40% from base load generators (steam turbine and combined cycle). This automatically limits the share of power from renewable energy sources to a maximum of 60%.

The results of this analysis include a decreasing rate of renewable energy share when installed capacity increases. Hence, an increasing rate of change is found between spilled energy and increased installed capacity of renewables. Carbon emissions, LCOE and fuel consumption are shown to follow the same trend: a decrease in absolute value at a decreasing rate when more renewables are installed. The introduction of EVs into the island power system shows positive results for all indicators in all scenarios, with significantly the greatest benefits when V2G technology is used. An interesting observation is that the doubling of the EV fleet has a smaller effect than moving from G4V to V2G.

In the case of emissions, when there is little renewable energy capacity installed, the introduction of EVs produce a higher level of emissions, because of increased electricity demand. This is corrected when more RES are installed. In numbers, when 50,000 EVs are introduced, the cost reduction for fuel imports is 23.72 M€ (~16%) and the reduction of carbon emissions on roads is estimated to be 124,830 ton CO_2.

As possibilities for follow-up research, the authors include the addition of unit commitment to the analysis and the comparison of uncontrolled charging strategies with other charging strategies. Moreover, a suggestion is made to evaluate the complementary aspects between pumped hydro and storage through V2G.

--

Pina et al. [98] analyse the introduction of EVs in the island of Flores, Azores for the time horizon 2010 – 2030. The authors assess how the penetration of EVs can influence the investment in new RES generation capacity, how much RES can be used for EV charging and what is the potential for reduction of energy use and emissions in the island from the shift to EVs. Specifically it looked to optimize the investment in new hydro generation capacity, although investment in new diesel generators is also possible within the model. The attempt has been to measure impact of two aspects on power systems: either a low or high penetration rate of EVs and a fixed or flexible time of recharging strategy. This can subsequently be used for the identification of time periods in which it is favourable to introduce EVs and which policies should be pursued to maximize their benefits.

A detailed temporal analysis is performed in two stages, a medium-term model and a short-term model. The medium-term model deals with capacity investment and planning of the power system. It is aimed to *"...optimize the investment in new generation capacity from RES by taking into account the evolution of electricity demand and fuel prices, over a time horizon of 20 years. The output from this model consists on the quantification of the installed capacity in each year, which is then used as input for a short-term model, electricity dispatch model."* This part of the bipartite model is developed in the software programme GAMS, and it is able to optimize by minimizing the system cost throughout the time horizon of the simulation. The short-term model deals with the dispatch of different electricity generators and the charging of the EVs. It is used to *"...optimize the balancing between electricity production from the different energy sources and electricity demand, as well as the time of day at which recharging EVs maximizes the use of renewable energy sources."* This part of the bipartite model is developed in Matlab. Since detailed data on vehicle usage is not available for the island, the authors constructed the EV recharging profiles based on Portuguese mobility patterns.

This study is limited to investigating the impact of optimised timing of recharging of EVs, as it does not deal with storage of electrical energy in EVs. The times of charging are dispatched to minimise operating costs of electricity production. The EVs are modelled as a group, not individually. Amount of energy needed for all EVs is spread optimally over day.

This study shows the potential that EVs have to improve the sustainability of power systems, by providing a continuous decrease in total CO_2 emissions. Numerical results show a reduction in primary energy for the island of Flores ranging from 0.2% to 1.1.%. For CO_2 emissions this figure is higher, from 0.3% to 1.7%. Flexible time of recharging strategy was shown to double the share of RE in the recharging of EVs.

The authors also indicate however, that it will require a *"...significant behaviour change, backed up by aggressive policies and economic incentives that would convince people to allow the network operators to decide the best times for recharging the vehicles.*

A simulation tool [99] has been developed in MATLAB to simulate and evaluate the impact of different EV penetration scenarios on the light-duty (LD) vehicle fleet. This model has been adapted and used in a case study for the island of São Miguel performed by Camus et al. [100]. Results of this model include:

- Daily electrical load profile [MW]
- Percentage of RE consumed [%]
- Electrical system CO_2 emissions [ton]
- Daily LD fleet CO_2 emissions [ton]
- Annual LD fleet energy use [TJ] and CO_2 emissions [kton]
- Global LD fleet and electricity production energy use [TJ] and CO_2 emissions [kton]

This research is aimed at investigating the impact of the integration of EVs into the island's power system, and specifically to answer the question: *"What level of EV penetration can justify an increase in geothermal capacity until 2020?"*

Five case-studies (scenarios) are investigated:

1. BAU without EVs, 2% increase in electricity demand and 9 MW of wind power by 2020
2. BAU without EVs, 2% increase in electricity demand and 9 MW of wind power and 10 MW of geothermal by 2020
3. Realistic scenario of 4000 EVs, 2% increase in electricity demand and 9 MW of wind power and 10 MW of geothermal by 2020
4. Optimistic scenario of 5900 EVs, 2% increase in electricity demand and 9 MW of wind power and 10 MW of geothermal by 2020
5. Adequate scenario of 9900 EVs, 2% increase in electricity demand and 9 MW of wind power and 10 MW of geothermal by 2020

The EVs are modelled as a group, not individually. Charging distribution is taken as uniform distribution and the charge profile is constructed to let most of the charging occur at off-peak hours.

The authors conclude, once more, that electrifying the car sector has the potential to decrease energy unit costs and oil import and reduce CO_2 emissions, by increasing local electricity produced by renewable sources. The simulations show that only for the fifth scenario with 9,900 EVs (15% of LD fleet), the accommodation of 10 MW new geothermal capacity is viable without putting the electric system at risk. The same is true for great reductions on energy and fossil fuel use: these are only achieved for the 15% replacement scenario. Moreover, it shows that running costs of a vehicle can be cut to 1/5 in the case when an EV is used, to a level of 1.4 to 1.5 €/100km, based on cost for a recharge of 11.6 – 12.3 cents/kWh. Interestingly, the authors do not expect a 15% LD fleet replacement by 2020.

--

Kadurek [35] identifies the potential for EVs to the three different power markets: (1) base load, (2) peak power market and (3) spinning reserves and regulation market, for the island of São Miguel in the Azores. The study optimises charge times to maximise EV owner revenues. The EVs are modelled as a group, not individually. Power is limited to a max of 20 kW for peak shifting and 25, 30 kW for peak shifting, spinning reserves and regulation scenarios. The economic analysis in this study is limited to the user perspective of controlled EV charging and V2G technology.

It concludes that base load is not competitive, but within the peak power market, an EV is able to generate a small amount of revenue for the user in the range of 179-261 euro/year, dependent on the daily range. However, this is only revenue and operational costs still need to be subtracted. Thus the possibility for EV users to connect their vehicle to the grid in order to supply peak power is deemed unattractive. For spinning reserves and regulation on the other hand, significantly higher revenues can be expected, in the range of 2848-4273 euro/year, dependent on the available line capacity of charging infrastructure. Results include the impact of different scenarios of EV penetration levels on the daily electricity demand curve for the years 2010, 2015 and 2020. In all cases the introduction of EVs is shown to flatten the demand curve by reducing its morning valley and evening peak. In the last case, a 20% penetration of the 55,000 cars fleet in the year 2020, the demand curve is almost completely flattened.

Denny [101] performs an analysis for the Aran islands (Ireland) in which a smart energy network is developed using a high-level approach through an energy optimisation model that considers *"electricity, heat, and transport demands as integrated loads rather than as distinct components and synergizes the usage patterns of certain flexible elements of the demand to coincide with available renewable energy generation and time of day prices."*

Special about this model is that it maximised the usage of local renewable energy sources instead of minimizing total system cost. The authors have optimised charge times to first maximise renewable electricity usage at fixed charge rate of max. 3 kW. The second objective is to minimise generation costs. The EVs are modelled as a group, not individually.

A total of five scenarios is analysed considering a base case, an efficiency case (with improvement in the energy efficiency on the island) and scenarios for added wind and wave energy capacity (from 50% to 100% penetration level) combined with EV and heat pump penetration levels from 50% to 100%.

It shows massive CO_2 reductions for the high penetration levels of renewable energy, cutting CO_2 emissions in less than half and close to zero for the 100% renewable energy case (only a small share remains for the heavy transport on the island). Part of the reason for this is the availability of a 3 MW power line connecting the island to the mainland and allowing for a net export of renewable energy.

This study recommends the investment in air-source heat pumps before electric vehicles, since this represents a significantly more economical approach to achieving a smart energy network than through electric vehicle deployment: the capital and O&M costs are only 15% of that of electric vehicles. Part of the reason for this is the current high and inefficient heat demand on the islands and the low transport demand.

--

Ilic et al. [102] have looked into the impact of controlled EV charging for the case of Flores, part of the Azores. A model is used to optimise charge times to minimise charge costs at a fixed charge rate of 3 kW and discharge rate of 1 kW. The EVs are modelled individually. An interesting observation is stated, it shows that the investment in new generation capacity, either wind or solar power, depends strongly on if controlled charging is applied:

"...in both the uncontrolled and the controlled EV charging scenario, it is better to invest in more wind capacity first. At some point, however, building more wind leads to much more spilled generation and it is better to diversify the generation mix by adding some solar, despite the fact that this is roughly two times more expensive. [...] In the controlled EV scenario, the EVs are able to avoid spilling energy much longer, so here it is beneficial to build more of the cheaper wind capacity." [102]

This shows the value of combining insights in the development of the EV fleet on an island and the new renewable energy generation that is planned.

As a response to negative notions on the cost effectiveness of renewable energy, mostly related to the spillage of energy during e.g. times of high wind, the authors conclude the following: *"When observing the cost effectiveness of these new renewable energy generation capacities, one should look at the levelised cost of electricity. These figures for wind, solar and diesel generation are roughly 100 $/MWh, 200 $/MWh and 250-300 $/MWh, respectively. This means that if 60% of all wind energy is spilled, it is still cheaper than diesel generation. For solar this is the case if 20% is spilled. These numbers strongly suggest that it does not only make sense to invest in wind and solar from an environmental point of view, but also from an economical."*

It was found that controlled home charging of 100% EVs with V2G capabilities in combination with a moderate wind and solar scenario allowed for significant reductions in curtailed energy, from 23% to 8%.

This study does not consider the use of EVs for automated generation control for frequency regulation or other ancillary services. Nor does it include ramping rates and start-up costs for conventional generators. This results in the situation where there is no spilling of wind or solar due to intermittency. In practice, due to cost and reliability reasons these diesel generators will not be switched on and off as frequently as simulated here. Other neglected issues in this research are the effects of EV charging on electricity networks and the impacts on reliability and dynamic stability, which could lead to spinning reserve requirement of back-up diesel generation.

Comparison of reviewed literature

The studies identified as core papers are evaluated on several key characteristics and compared to this thesis. These characteristcs are 1) influence on residual load curve 2) unit dispatch of generators, 3) comparison of uncontrolled vs. controlled charging, 4) investigation of vehicle-to-grid technology, 5) individual modelling of EVs with unique drive cycles, 6) 4) the analysis of a flexible power rate per EV, 7) evaluation of charging infrastructure and control options, and 8) evaluation of technical performance vs. economic potential. Moreover, the modelling tool used in the analysis is given for each of the core papers. This is depicted in Table 3.2.

Table 3.2 Comparison of research characteristics of core papers and this thesis, showing the main contribution of this thesis which involves analysing the impact of different charging infrastructure and control options, and comparing technical performance to economic potential.

Characteristic	Diaz	Pina	Camus	Kadurek	Denny	Ilic	Thesis
Influence on load curve and renewables integration	V	V	V	V	V	V	V
Unit dispatch of generators	V	V	.	.	.	.	V
Uncontrolled vs. controlled charging	.	V	.	V	V	V	V
V2G - peak shaving	V	.	.	V	.	V	V
V2G – spinning reserves	V	.	.	V	.	.	.
V2G – frequency regulating	.	.	.	V	.	.	.
EV modelled individually with unique drive cycles	.	.	.	.	.	V	V
Flexible power rate per EV	.	.	.	.	.	.	V
Evaluation of charging infrastructure and control options: - only home vs. public & home - low power vs. high power - G4V vs. V2G	.	.	.	.	.	.	V
Evaluation of technical performance vs. economic potential	.	.	.	.	.	.	V
Modelling tool	MATLAB	GAMS+ MATLAB	Custom MATLAB	MATLAB	EXCEL	MATLAB	MATLAB

3.3 Positioning of the thesis

This thesis builds upon the literature described in the previous section that has investigated the role of EVs within future island power systems. It analyses a future island electricity system with a high-penetration of wind and solar generation in combination with a large electric vehicle fleet to provide system level insights. More specifically it will follow a similar approach to Ilic et al. [102] as it will in detail model the behaviour of individual EVs with cost optimisation of their charging process.

This study adds to this small body of literature on smart charging and integration of electric vehicles in islands with a high penetration of renewables, and sets itself apart from part of the existing literature in the way that it, conversely to current research,

- Provides a comparison of the full spectrum of options for charging infrastructure, including controlled (smart) charging and a high power infrastructure. Moreover, it evaluates the implementation of vehicle-to-grid technology, which allows for the use of EVs for peak shaving;

- Where previous research assumed charging infrastructure to be present, this study compares the technical benefits of adding controlled EV charging, V2G technology, public and high power infrastructure to the costs involved to actually implement these infrastructure options and renewable power generation in an economic analysis.

- Combines individual EV modelling with the implementation of a unit dispatch model. This way it analyses the impact of both day- and night-time charging through the addition of public charging infrastructure, in combination with real driving cycles to determine when a car is on the move and thus can or cannot charge. Consequently, the impact on conventional base load power production and dispatch of each specific generation source and spinning reserve constraints are shown;

This study involves the generation of results and therefore insights on a system level. It does not entail a detailed analysis on grid impacts of EV charging, design of smart power control strategies or long-term impact of EV integration. These insights are attained by investigating the impact of different charge and discharge control scenarios on key indicators. It thus constitutes an exploration of the technical and economic potential for flexible demand and storage.

The actual implementation of these scenarios and the realisation of its performance is explored through a case study. The results are based on data gathered from field-research and conversations with experts on Aruba. The model is specified to the case of Aruba, but can be altered to represent any island with similar characteristics. Additions to the model are needed for islands with e.g. other forms of power generation.

--

This research is part of a research group within the common theme: *"Transition towards a Sustainable Energy Supply for Islands"*. Other topics of research within this group deal with the determination of cost-optimal electricity system configurations and the inclusion of ocean energy sources as part of the future energy mix for islands.

4. CASE-STUDY

4. CASE STUDY

In this chapter the motivation for the choice of the case-study island is presented. In addition, an overview of the collected information regarding the energy and transport system is provided. The aim of this research is to move from a more general analysis of different islands in the world through a common database to a more specific case study performed for one island, leading to insights and advice for the development of plans for the smart integration of electric vehicles and renewable energy. From this case-study more generic conclusion will be taken that can be applicable to other islands.

4.1 Choice of island

To the purpose of analysing and comparing different islands in the world, a database has been made of island within the population range between 10,000 and 1,000,000 inhabitants, culminating to a total of 296 islands. [141]. The database contains basic characteristics of each island, such as population, area and highest elevation. Furthermore the islands are categorised per ocean and in some cases states as part of an island group or archipelago. Figure 4.1 depicts these islands and their geographical location on the world map.

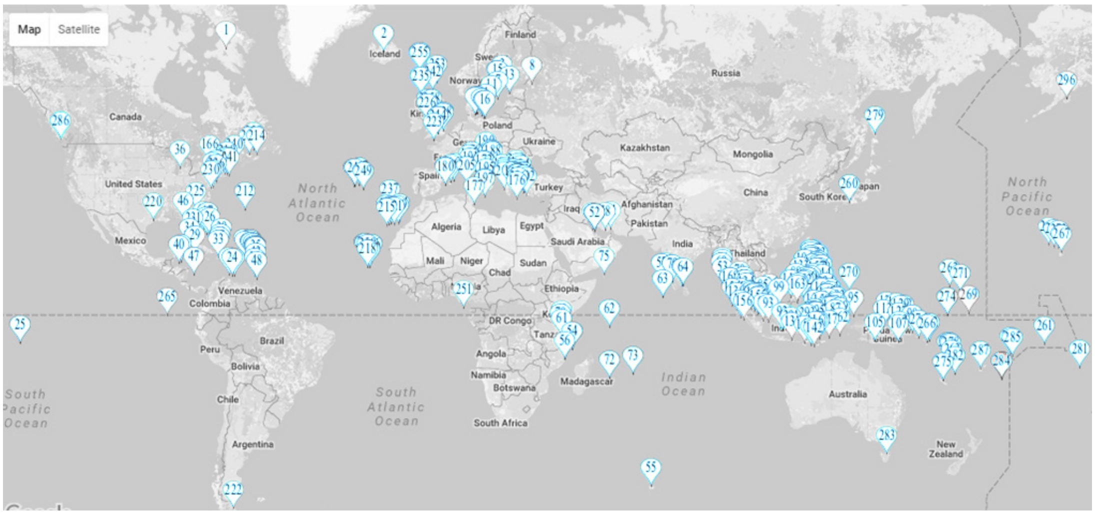


Figure 4.1 World map showing the 296 islands included in the database [141].

Several factors have been used in the assessment of a suitable case-study island. These include that the island has or is:

- representative for a larger group of islands or larger group of people
- no grid connection to the mainland
- largest, and thus most energy consuming island in archipelago
- includes most (conventional) power generation technologies
- data availability on grid operation
- data availability on travel routines of drivers
- (potential for) a growing EV market
- technologically advanced and able to set up smart charging infrastructure
- a stable political environment
- a long-term plan for transition to renewable energy
- commitment to making long-term investments in new technologies
- open to the implementation and experimentation of new technologies
- keen to collaborate with external parties and international organisations

Firstly, a categorization is made of the population per island. In figure 4.2 the amount of islands per population category are given. In this case several population ranges are defined for the purpose of general analysis and comparison. Naturally different ranges will produce different results, but these ranges have been found to be generally representative.

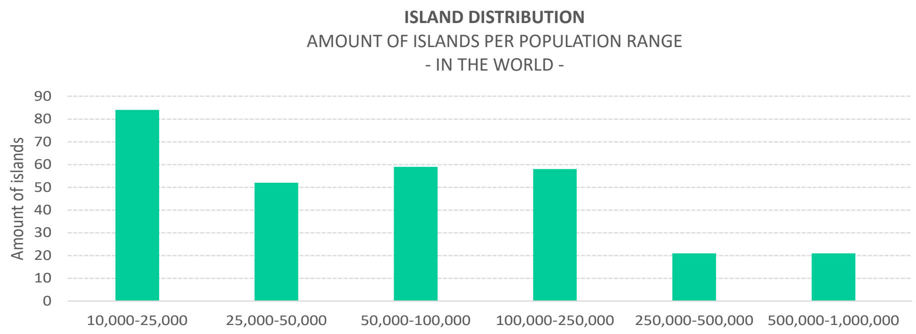


Figure 4.2 Overview of the amount of islands per population range

From this categorization the following conclusion can be drawn; there exists an inverse relation between the amount of islands per category and island size. In other words, the smaller the island, the more there are in the world. However if the possible impact of a certain study or technology is to be estimated, it is more interesting to determine in which category the majority of people live, and thus what the focus of the research should be. If the total amount of people per island category is analysed, the following is visible; the majority of islanders in the world live on the largest islands in the range of 500,000 to 1,000,000. Again there is an underlying trend visible, a larger sum of people live in the larger islands compared to the smaller ones. Figure 4.3 depicts this relation.

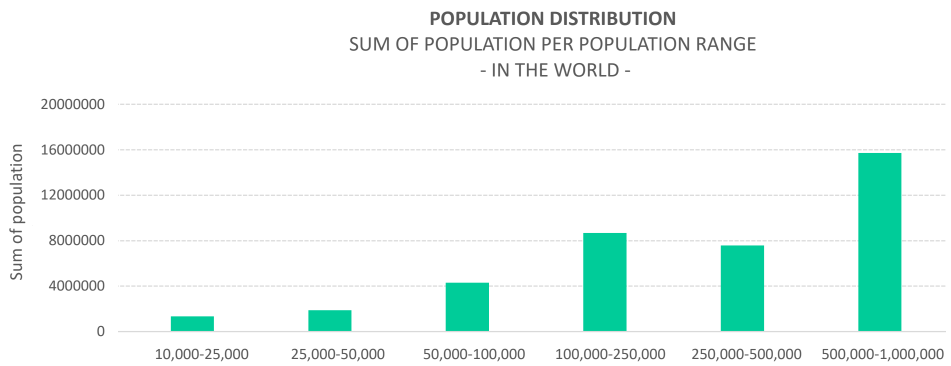


Figure 4.3 Overview of the sum of population of islands per population range

Comparison of the Caribbean islands

The first step has been to focus merely on the islands formally called the Caribbean part of the Kingdom of The Netherlands, or informally called the Bovenwindse en Benedenwindse eilanden. This island group has been chosen since there are strong historical ties to The Netherlands and thus many collaborative efforts between governments, but also companies. This connection benefits the islands and gives them an advantage compared to other islands in the region. In general, islands with ties to European countries are found to make the move to renewables more quickly than others [103]. The island group consists of the countries Aruba, Curacao and St. Maarten, and the special municipalities Bonaire, Saba and St. Eustatius. These last three are the so-called Dutch Caribbean. An overview of these islands is given in figure 4.4.

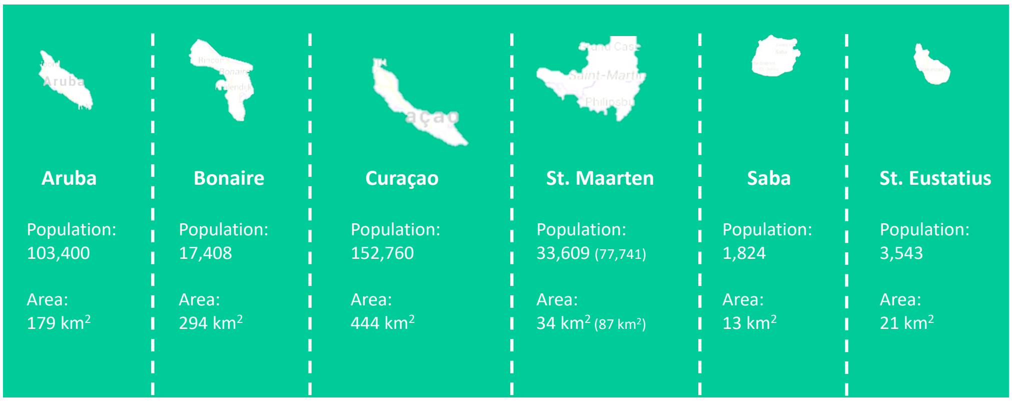


Figure 4.4 Overview of the characteristics of the islands in the Caribbean part of the Kingdom of The Netherlands.

The following insights into the specific situation of the islands under consideration and their impact on technological innovation in the field of renewable energy have been collected through an interview with an expert energy consultant operational in the region [105].

Aruba

The wealthiest country in the Caribbean – its GDP per capita is with 23,353 USD per year the highest after the Bahamas and Trinidad & Tobago [106] - and is therefore in the position to be an innovator in many fields. The country has experienced a stable political climate over the last decade. This, among other reasons, has allowed the country's government to set an ambitious goal in terms of transition towards renewable energy. Currently roughly 80% of the electricity consumed comes from fossil-fuel based generation including steam turbines and reciprocating engines, but it aims to use 100% renewable energy (electricity) in 2020. To that effect it has created a platform where it receives help and advice from international institutions such as the Carbon War Room. During the last years it has started to develop tracks to achieve this goal and putting plans into action by investing in renewable capacity, such as a 30 MW wind park at Vader Piet and a 3.5 MW solar power plant at the airport, the largest Caribbean solar power source [107]. Every year a Green Aruba Conference is hosted during which important stakeholders and experts from over the world get together to discuss the way forward for Aruba and the World in the field of green technology. It sees itself as a knowledge development hub for the region. Furthermore, with its relatively large population of 103,400 it is representative of the island ranges with the largest populations in the World.

The country has seen a gentle increase in the sales of electric vehicles on the island. This can partly be dedicated to the reduction in import duties for hybrids and full-electric vehicles. The Aruban government is looking for more ways to accelerate the uptake of emission-free vehicles. Both utility companies are focussing on the installation of charging infrastructure required to facilitate the transition to electric mobility.

In order to construct a realistic model of the power system of an island, and future scenarios for the implementation of renewable energy, a location with ample available data is a must. Aruba's utility companies dispose of this data and have been found willing to share this with external parties. National energy producer WEB Aruba has recently published an online dashboard in which the real-time production and share of electricity from different resources is presented for the current day [108].

On Aruba a Smart Community [109] will be built as living lab for innovations in the fields of water, waste and energy. This collaborative project involves a consortium of the Aruban electric and water utilities WEB and ELMAR, communication company SETAR, the housing development foundation FCCA, government of Aruba and the TNO Caribbean branch office. This community will consist of 20 homes that will be used to test and showcase new technologies in a real-life setting. The existence of TNO's branch office on the island is seen as another key element that will help in communication to and between the various stakeholders in both this research as well as the future implementation of smart integration of electric vehicles.

Bonaire

Although the second largest island of the selection, Bonaire has the smallest population. Being a special municipality of the Netherlands, the communication to the island may prove to be easier from the Netherlands and it provides a strong connection with the Netherlands and Europe in general, where many countries have incorporated large amounts of wind and other renewable sources of electricity. Since it launched its clean energy initiative in 2005, Bonaire is pressing forward in the field of renewable energy as indicated by the Rocky Mountain Institute [103]. *"The island is now home to 12 wind turbines with a total of 11 MW of wind power capacity, which contribute up to 90 percent of the island's electricity at times of peak wind, and 40–45 percent of its annual electricity on average."* After its diesel power plant burned down in a fire, Bonaire took this event to its advantage and has been working at the implementation of large-scale wind power, battery storage and biodiesel produced from algae grown in the island's large salt pans. The island has recently received an offer to implement charging infrastructure, but has not accepted. This is possibly due to the fact that financially it is not doing well and provides little transparency. The island remains under supervision of the Dutch government. The future of electric vehicles on the island is insecure, there are no plans for their implementation.

Curacao

The last years this island has experienced political and financial instability. This has resulted in the fact that there is little to no attention for long term plans regarding the energy transition. However, the island did consider applying for a sustainable energy subsidy from Dutch government, but it is far behind on the process. Electric vehicles are not a part of this plan, the country focusses on the use of liquefied petroleum gas (LPG) to reduce emissions of its vehicle fleet.

St. Maarten

A small and densely populated island. It is divided into two territories, a French part and an independent country that is part of the Kingdom of The Netherlands. This island is relatively poor and thus there is little focus on the reduction of CO_2 emissions. This island can prove to be difficult to communicate with since its divided political structure.

Saba & St. Eustatius

Due to their small population size, Saba and St. Eustatius are excluded. Their populations of 1,947 and 3,193 inhabitants in 2016 [104] are deemed too small to be representative.

Choice for Aruba

The aforementioned characteristics have led to the choice of Aruba as the case-study island for this thesis. It is believed that insights and solutions developed for Aruba can be expanded to other islands in the region and ultimately in the world.

4.2 Aruban power system

This section will provide an overview of the characteristic of the Aruban power system. A general overview of its characteristics is presented in figure 4.5, based on [110].

TOTAL INSTALLED CAPACITY	230 MW
PEAK DEMAND	140 MW
TOTAL GENERATION	920 GWh
RENEWABLE SHARE	18%
PROPOSED/PLANNED RENEWABLE PROJECTS	35 MW

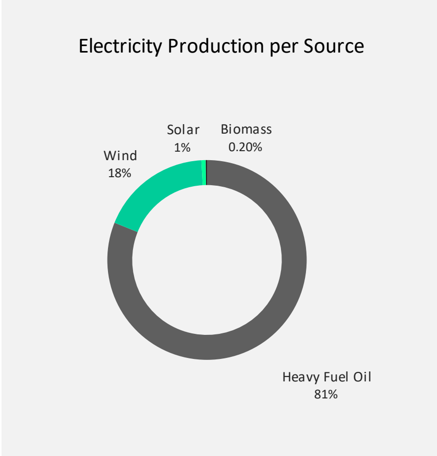


Figure 4.5 Overview of the Aruban power system [110].

The energy imports on Aruba are mainly used for electricity generation (67%), the other shares are in decreasing order the transportation sector (29%) and gas used for industrial and household heating and cooking (4%). This is data for the year 2013 from [111] and constructed by combining representative data for 2013 from the UN Statistics Division Energy Statistics Database, the Aruban Central Bureau of Statistics and WEB Aruba. The use of different sectors on Aruba is roughly divided into three equal shares in the categories residential, small commercial and large commercial energy usage [112].

Utility structure

Aruba's utility structure is based on a government owned monopoly. Utilities Aruba NV acts as a holding company for the separate generation and distribution companies:

- WEB Aruba NV: 'Water en Energie Bedrijf Aruba NV' is in charge of the production of water and electricity on the island. They are tasked with power and water production and water distribution.
- ELMAR NV: is the grid operator and electricity distribution company. They are responsible for the distribution and maintenance of the distribution system.

The current consumer (tier 1) price tariff is a standard flat rate of 0.45 AWG, or 0.225 EUR, per kWh [113]. There is no distinction between a day / night tariff. The electricity grid operates at a standard outlet voltage of 120 V and a grid frequency of 60 Hz. Most homes however are equipped with a 240 V outlet, for e.g. an air-conditioning unit.

Electricity demand

The electricity system of Aruba is currently characterised by an approximate 107 MW average production, although a multi-year estimate of 100 MW has been widely used in communication. These numbers result in 934 and 876 GWh of energy consumed per year. Only 779 GWh of this produced electricity is delivered to consumers, the rest can be accounted to grid transmission and distribution losses [111]. In the remainder of this thesis, the power demand as seen from the power generation side, so the sum of consumption and grid losses, is considered.

Aruba thus has relatively high electricity use per capita, with an annual average of around 8,000 kWh used per person in recent years [112]. This is roughly two to three times more than neighbouring island Curacao [114]. A higher quality of life standard and significant tourist numbers contribute to this difference.

The electricity demand of Aruba per year with weekly averages is presented in figure 4.6. The demand is partly correlated to the population on the island, influenced by tourist numbers which in some months can almost double the population of the island [115]. Unfortunately, no tourism data has been available for the year 2015 at the time of writing, so this correlation is not shown here.

Furthermore, air temperature and electricity demand have a strong correlation due to the widespread use of air-conditioning systems on the island. This correlation is presented in figure 4.6. The ambient air temperature has been normalised around a value of 100 (approximate average of yearly demand). Although August is high season for tourism and in September tourism numbers drop considerably (based on historical data), a continued increase in electricity demand through the month September is visible. This may be attributed to the effect that during this month the trade winds slacken [116] and the air temperature is at its highest. Thus resulting in an increase in electricity consumption, mainly from air-conditioning.

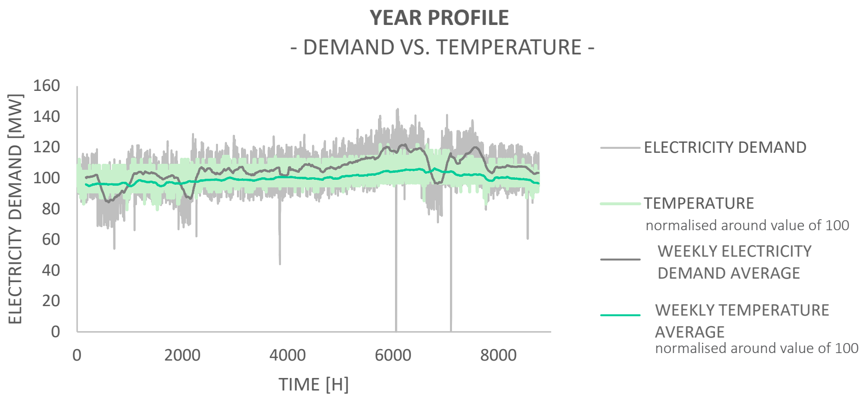


Figure 4.6 Comparison of demand profile and temperature values, the latter normalised around a value of 100 (approx. avg. of yearly demand).

The three distinct valleys in January, March and October with their sharp decreases in average power demand and several very low values (even to zero) cannot be explained through these correlations. WEB Aruba indicates that these are faults in the data [117]. In further analysis these negative spikes are manually removed from the data since actual demand will not drop as such and we are interested in the average case, not incidental events. The valleys in the three months are not changed and kept as provided, but these time periods will not be analysed in more detail.

Daily variations in demand for a typical week are depicted in figure 4.7. What can be seen is that on each weekday, two peak periods exist: one during the day and one during the evening. In between these, around morning and evening rush hours, there are two clear dips in demand. This is due to the fact that the majority of people are in their car on their way to work or to bring their children to school. Demand decreases during the period from midnight to morning until it rises sharply again due to start of daily (economic) activity. Furthermore, demand in weekends differs, Saturdays more or less resemble weekdays but Sundays are clearly different as they do not possess the day peak, solely the evening peak, since there is little industrial and business activity.

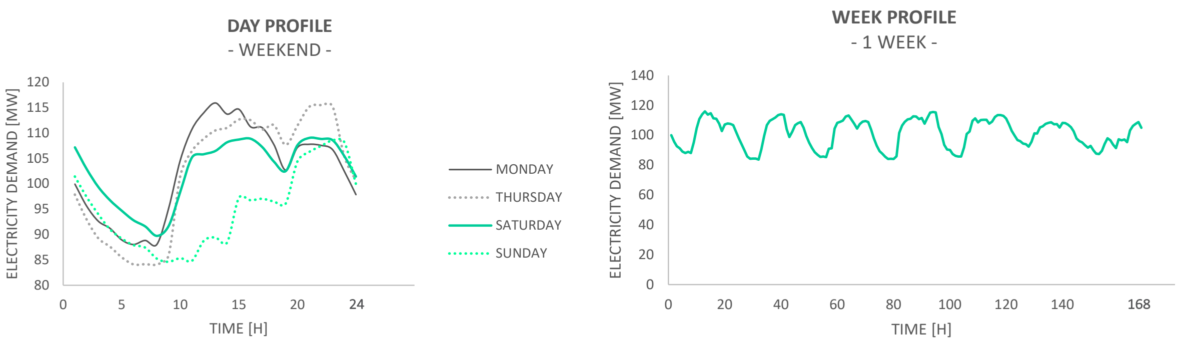


Figure 4.7 Aruba's electricity demand profile for several days of the week (a) and for a whole week (b).

Demand breakdown

Figure 4.8 presents the same data of electricity usage, based on [111], now divided per type of use (in TJ) and the shares of fossil fuel based generation and wind power of used energy and primary energy[4] in percentages.

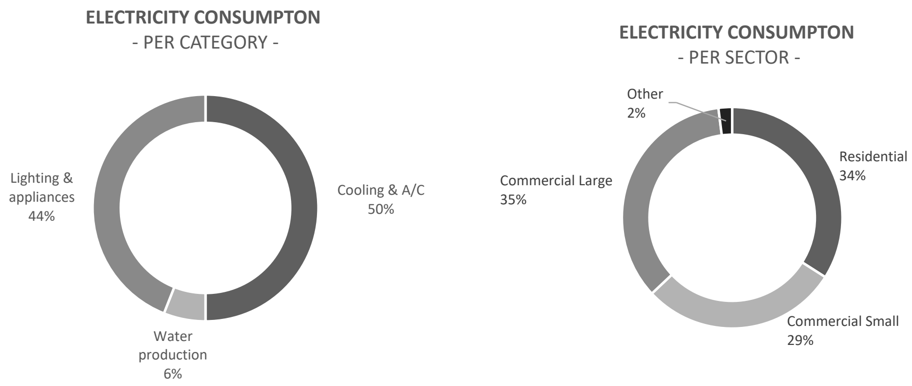


Figure 4.8 Aruba's electricity usage per type of use (a) and consumption per sector (b).

Power production

WEB Aruba, the national power production company, employs around 350 people, with another 150 contracted. Their facilities include 2 powerhouses and a set of desalination plants. Their powerhouses include the following set of heavy-fuel oil based generators: steam turbines and reciprocating engines. A single separate gas turbine is recently acquired. The steam turbine generators, or thermal power production (TPP) units, are used to provide base load power. Together they provide up to half of the average demand. The set of reciprocating engines cover the remaining share. At the moment, the gas turbine has a negligible role in the production of electricity.

In terms of renewable energy production, two main projects currently contribute to the power supply. Firstly, at Aruba's international airport, 14,000 solar panels are installed that cover the entire parking area. This entails a 3.5 MW installed peak capacity, which provides energy equivalent to the demand of roughly 500 homes. Secondly, a wind farm has been put in place in 2009 on Aruba's north shore that consists of 10 Vestas 3 MW turbines [107].

As back-up power supply a single 20 MW diesel generator is available. Conversely to the reciprocating engines, this generator runs on clean diesel fuel and thus has its own separate fuel stock.

The full set of power production technologies is presented in table 4.1 [117,118].

Table 4.1 Power production technologies currently installed on Aruba.

Type	Specifications	Output power
2 Thermal Power Producers	2x 30 MW	60 MW peak combined
10 Reciprocating engines	4x 11.3 MW 6x 7.8 MW	92 MW peak combined
1 Gas turbine	1x 22 MW	22 MW peak
1 Back-up diesel generator	1x 20 MW	20 MW peak
10 Wind turbines	10x 3 MW	30 MW peak combined
1 Solar PV park	14,000x 250 W	3.5 MW peak combined

Implementation of renewables

In 2008, WEB Aruba has started with preparations for the integrating renewable energy into their production mix and in 2009 the Vader Piet wind park came partly online. Several other renewable energy projects are planned, these are summarised in table 4.2 [121]. The ultimate goal is to maximize the share of sustainable energy, but with regard for constraints of cost and reliability. This decision making process is summarised in the so-called RAS framework [107], taking into account Reliability, Affordability and Sustainability. A timeline showing the growing renewables share is shown in figure 4.9.

Table 4.2 Planned renewable energy projects on Aruba [121].

	Installed Capacity (MW)	%	Expected Yearly Yield (MWh)	%	Operational?
Aruba Demand	100	100%	920,000	100%	-
Wind Park Urirama	24	24%	84,100	9.6%	No (stalled)
Waste-to-Energy (Gas)	5	5%	43,800	5%	Partial
Residential and commercial Solar PV	6	6%	10,950	1.3%	Partial

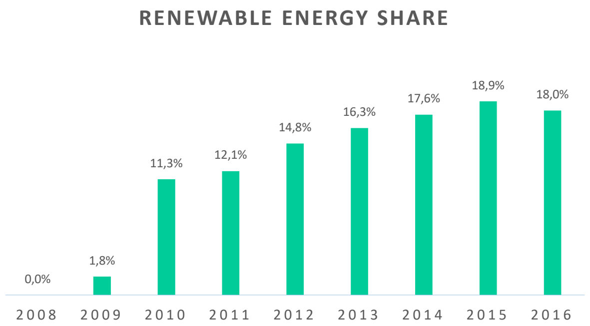


Figure 4.9 Timeline of growing renewable energy share, as part of electricity produced.

A short descriptive paragraph is provided as background information for each of these projects.

Wind Park Urirama

This wind farm is planned to be the follow-up from the existing Vader Piet farm. The initial plan was to double the installed wind power capacity, by installing another 30 MW of wind turbines. As a first alteration, the farm was downsized to 24 MW. On top of that, it has met with severe civilian protest regarding visual pollution and its implementation is therefore stalled. If the project gets the green light, installation can start presumably straight away as it is ready for development [107].

Waste-to-Energy (Gas)

The goal is to use gas from a pyrolysis based waste-to-gas plant as fuel for the gas engine and/or the steam turbine. The estimation is that there is a 10 MW potential for Aruba. In the first phase, the plan is to develop a system that can supply around 5 MW of nearly constant production. At the moment, the production of gas from waste is still in the pilot phase and not yet able to supply a constant fuel flow.

Residential and commercial Solar PV

In addition to the large-scale solar PV park at the airport, small-scale solar is also planned. This includes panels on commercial buildings, schools and homes. A total of 6 MW installed peak capacity is estimated to be installed within the next years of which 4 MW on school rooftops.

Power dispatch

Power system frequency is set by one thermal power production (steam turbine) unit operating in frequency (isochronous) mode. The remaining online units operate in droop mode. This control setting provides a stable working point for each generator in case of parallel operation by increasing the fuel feed as the turbine/engine slows down under load, and vice versa. Furthermore, the reciprocating engines are started and stopped to maintain sufficient spinning reserve capacity as load increases and decreases [119]. For example, at night, several engines are switched off because of the valley in demand and are started up again the following morning.

Voltage is controlled with automatic voltage regulators (AVRs) on every generation unit. These maintain system voltage by either increasing or decreasing reactive power produced by the generating units dependent on the system power factor [119].

This dispatch is depicted in figure 4.10 for a day with stable wind power generation (4.10a) and for a day with unstable wind power generation (4.10b) [118]. It also indicates a moment where wind power is curtailed due to too much wind swings, i.e. the production ramps of wind power output are too large, leading to grid stability issues. It should be noted that wind power can only be curtailed for a certain amount each year, based on the specifications of the contract.

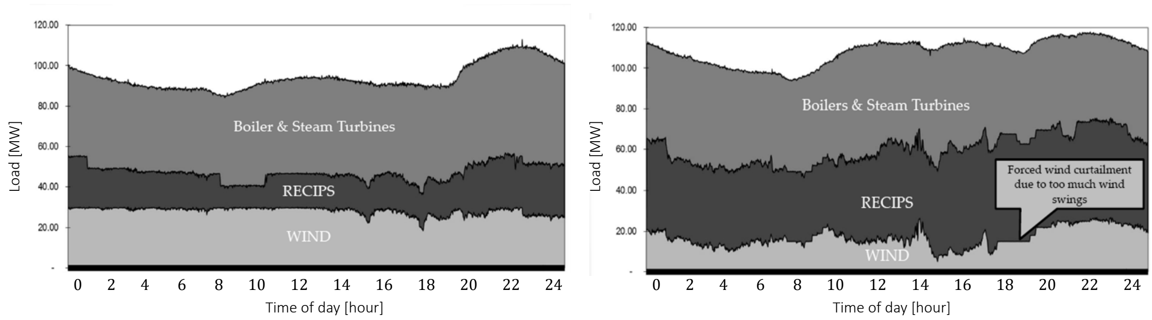


Figure 4.10 Dispatch of a single day with a stable wind resource (a) and a day with unstable wind generation (b) [118].

In 2011, to be able to facilitate an increasing share of renewable energy and reduction of emissions, investments have been made in newer and larger reciprocating engines. These are the four 11.3 MW reciprocating engines. These engines are air-cooled and part of their waste-heat is recovered to produce steam. This brings their combined efficiency up from 45% to about 60%. This steam is used either to preheat the fuel or as input for the steam turbines. These newer engines are gas-ready. Currently, the gas turbine is only used for a small share of power production at 0.15% for 2015 [117].

To ensure system reliability, Monte Carlo simulations are run for all generating units, based on a loss of load expectation (LOLE) predictions [119]. These calculations are used to see how much of the produced solar and wind power can effectively be incorporated into the grid. The reserve requirements used in this calculation depend on the time of day, week or season.

Emissions

These steam turbines and reciprocating engines currently use heavy fuel oil (HFO) as fuel. The estimated fuel consumption for the current situation - excluding the airport solar park and waste-to-energy plant - related to electricity and water production is around 3700 barrels/day [113] and CO_2 emissions are around 1800 ton/day [118]. This amounts to a value of roughly 750 g CO_2/kWh (using an annual production of 876 GWh). This value corresponds well to the reported value for HFO-based electricity generation as will be discussed in section 5.8, however does not include life cycle emissions.

Other developments

When, or maybe rather if, the new Urirama wind farm becomes operational, it is indicated in [107] that *"a sudden drop in wind power could easily result in a drop in production of as much as 25 MW, with conventional power production needed to absorb this drop. The slow ramp-up time of the heavy fuel oil-powered turbines also means that there may be some delay before this back-up supply fills the gap. Storage is the only way to resolve this issue."* Thus stating the need for storage to accomodate these wind power fluctuations. Naturally this depends on the time frame in which these drops occur. One could argue here that storage is not the only solution, and fast-response generators could for example be an alternative solution to meet these needs.

Two storage options are explored, these include the installation of a flywheel system and a modular underwater compressed air storage system. In its current state- phase 1 – the flywheel is able to supply 5 MW for about 12 minutes, indicating an energy storage capacity of 1 MWh. The compressed air system situated at San Nicholas will be able to supply 1 MW of power for a duration of 8 hours, thus culminating to an energy storage capacity of 8 MWh. Both systems have been contracted [123]. A collaboration has been set up with Tesla Energy to work on the implementation of a stationary battery system to help in grid balancing.

Another key development is the implementation of an automatic generation control system. Currently, the reciprocating engines are manually operated, meaning that every change to their power output is a manual adjustment. This AGC system should be operational in 2018/2019, before the second planned wind park will be online.

Several of the generators have been adapted over the last years to be able to use gas as a fuel source. WEB Aruba will be using gas as a more prominent fuel source in the future. According to calculations of WEB Aruba the realistic limit – taking into consideration reliability and affordability – of intermittent renewable energy integration is in the range of 40-60%. Therefore, the company has developed a strategy to move towards 50% share of renewable electricity and 50% gas-based generation in 2020 [120].

4.3 Aruban transport system

The transportation sector on Aruba uses approximately 29 percent of imported fuel [111,112]. The focus of this research is on the impact of the electrification of personal vehicles and how the smart integration of these can aid in the increased share of renewables. Therefore, the other types of vehicles on the island are excluded from the survey, these include busses, trucks, heavy equipment, etc.

Personal vehicle fleet

Aruba is characterised by a very high car ownership, roughly 1 vehicle per 2 inhabitants. All cars on the island are – like almost any product on Aruba – imported. Since there is no connection to shore or a ferry service, the cars stay on the island during their ownership. The amount of personal cars on Aruba is depicted in table 4.3. It provides numbers of vehicles per type and their estimated average yearly distances [124].

Table 4.3 Overview of the amount of personal vehicles and their respective estimated kilometrages on the island of Aruba [124].

Personal vehicles	Private	Rental	Government	Taxis
Numbers	49,000	3,600	400	400
Kilometers/year	15,000	17,500	10,000	25,000

Emissions

Total daily consumption of gasoline and diesel fuel on Aruba in 2011 is 1,284 and 533 barrels respectively [121]. Emission from transport are calculated to amount to 266 kton of CO_2 each year, of which 60% is related to personal cars [125]. In a TNO study [124] from the year 2014, CO_2 emissions from personal cars on Aruba were estimated to be in the range of 260 to 390 g/km, significantly higher compared to the stated Dutch average stated in the report of 175 g/km. The reasons for the high emissions value on the island is lack of restrictions on or standards for vehicle emissions, a relatively high fraction of light trucks (SUVs), continuous use of air-conditioning and poor quality gasoline fuel [124].

Shift to electric mobility

To tackle this issue and decrease the emissions in the transport sector, the national government has reduced the import duties for hybrid and full-electric vehicles. According to the Carbon War Room [112], *"The ultimate goal for Aruba should be to achieve high penetration levels of EVs."*

At the moment there are about 50 full-electric vehicles on Aruba, of which 21 were sold by a company named Activated Power. This company is part of an engineering firm that has started to diversify their activities by selling certified pre-owned vehicles with low-mileage (5-10,000 km). These cars are mostly built around 2014-2015 for the North American market and sold on the island for a price of 30-35,000 AWG (15-17,500 EUR), roughly half their original selling price. The models sold include Nissan Leaf, BMW i3 and the electric Ford Focus. Even though this last model only supports Level 1 charging (~1.5 kW slow charging from home wall outlet) it is after the Leaf their most widely sold product. The reason indicated is its design and affordability. Newer Nissan Leaf models, starting 2014-2015, are equipped with larger - 30 instead of 24 kWh - batteries and "Lizard" heat resistance technology [127]. This technology has been proven to be crucial to prevent premature capacity fading in Aruba's hot climate and its previous home in e.g. the south of the USA.

Compared to internal combustion engine (ICE) vehicles, running costs for EV are lower due to reduced license plate cost and lower maintenance and 'fuel' costs. Estimates indicate fuel consumption costs of roughly 8 AWG (4 euro) and 20.4 AWG (10.2 euro) per 100 km for an EV and a gasoline vehicle, respectively [128]. These prices are calculated using the standard tariff of 0.45 AWG (0.225 euro) per kWh and a 0.17 kWh/km consumption.

If the same chart is made as in section 4.2, however now with all energy consumed by transport (excluding international tranportation) converted to electricity demand, the following is visible. This exercise estimates the influence of a complete transition to electric domestic mobility. Shown in figure 4.11, it can be seen that in the new situation roughly a quarter of the electricity demand will come from electric mobility [111]. This value is based on a 70% tank-to-wheel efficiency.

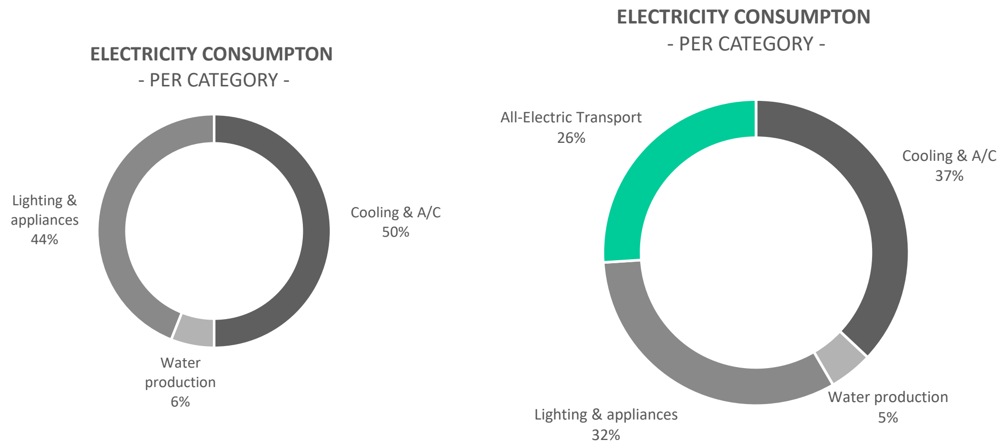


Figure 4.11 Current electricity consumption distribution (a) and hypothetical distribution including all-electric transportation (b).

This change would constitute an increase in electricity consumption of 35%. In [33] is written that the impact of such a large number of vehicles is *"...more than enough to overload existing systems."* Surely this will be the case for Aruba when all vehicles are charged simultaneously when they arrive home at the end of the day. Include the effect of an increase in power from solar energy, and the same future situation as in California is predicted (see figure 1.8 showing 'the Duck Curve' for the State of California). However, turning this challenge into an opportunity, a very simplistic calculation shows the potential of the synergy between solar power production and EVs. For Aruba, a valley of 50 MW could be filled with 5,000 EVs (= 10% of personal vehicles) using 10 kW chargers.

The business case for an electric lease car was considered in [28] for Aruba. In this study an electric Ford Focus (EV) and a Ford Taurus (ICEV), similar in terms of type, size and comfort, were compared. It was found that, in order to break-even with the ICEV, the monthly lease price of the EV will need to decrease with 8%, at 12,000 km per year. In a study [124] performed in 2014, it is stated that a full-electric vehicle does not prove to be competitive with a comparable ICE car, mostly due to an initial cost that is 1.6 to 1.8 times higher (considering import duties) and uncertainty about its residual value after five years or more.

Charge levels

At this moment, most EV owners charge their vehicle through a standard 120 V power outlet. Faster charging at home or at work is possible by means of a 240 V connection with a separate breaker and separate charge equipment (EVSE). Generally, it is expected that *"In the long run, 80 to 85% of charges will occur at home."* [129]. For Aruba this means mostly 1.5 kW charging during the evening and night, since Aruba has the US standard voltage outlet. This differs from the standard home outlet power of 3.5 kW available in Europe. Therefore, the denomination of charging power levels on Aruba also differs from that in Europe. The different power levels for both standards are depicted in table 4.4.

Table 4.4 Overview of different electric vehicle charge levels, both for Aruba and for Europe.

Power level	**Aruba**	*based on:*	**Europe**	*based on:*
AC Level 1	1.75 kW	120 V, 16 A	3.5 kW	240 V, 16 A
AC Level 2	7 kW	240 V, 32 A	17.5 kW	240 V, 80 A
DC Level 3	> 50 kW	500 V, 100 A	> 50 kW	500 V, 100 A

These power values are indications, the actual output depends on the maximum breaker current and the charger efficiency. Therefore, table 4.4 indicates with what voltage and current values these power levels have been calculated. Level 2 charging is based on high-power circuits (240 V, 32 A) that are standard in most homes. Level 1 and 2 uses the on-board charger of the EV, Level 3 uses an off-board charger. A general charging efficiency of 92% [130] is used.

Charge connectors used are US standard (type 1) for Level 1 and 2 charging, and CHAdeMO (type 4) for Level 3 fast-charging. On the island there are two fast charging stations, one in Hato and one in Noord. The station at Hato has one 50 kW DC charger and one 7.2 kW AC charger. Currently this public charging is provided for free, in order to motivate the (electric vehicle) market. In the future, when there are more than 5000 EVs, this will be a paid service. There are ongoing negotiations for future charging stations spread over the island. Plans are for them to be installed in Paradera and Savaneta. Activated Power [128] indicates that fast-chargers (> 50 kW) need to be installed on the island at three strategic places: Hato, St. Nicolas and St. Cruz, to provide sufficiently spread coverage. Supermarkets and other retailers are considering to implement slow chargers to attract customers.

Driving characteristics

In order to construct daily charge profiles for each EV data is required of their daily driving distances, average energy consumption per kilometre driven and departure and arrival times at home and/or at work.

Detailed information on mobility and driving characteristics is currently non-existent on the island . However a study has been conducted that has investigated the distances between home and school for attenders at all schooling levels and between home and work for the employed population of Aruba. This data gives insight into the relation between home region and distance to work for the employed population. Its main characteristics are included in appendix 2a.

Current 'normal' users indicate that at an average daily driving distance of 40-45 km, charging once every two days meets their energy needs. Others that cover larger distances (> 100 km/day) such as for business purposes, need to charge every night and if possible charge a bit extra during lunch. [128]

On Aruba, regular driving can be characterised as city driving, as the average vehicle will spend little or no time in 'highway driving' [112]. Due to its hot climate, air conditioning is standard in most cars and used constantly.

To give an estimate for daily driving distances, table 4.3 is expanded to include the amount of kilometres per day based on the yearly average and driving each day of the week, and depicted as table 4.5. Unfortunately there is no data available about specific departure and arrival times of Arubans at home and at the workplace.

Table 4.5 Overview of the amount of personal vehicles and their respective daily driving distances [124].

Personal vehicles	Private	Rental	Government	Taxis
Numbers	49,000	3,600	400	400
Kilometers/year	15,000	17,500	10,000	25,000
Kilometers/day	41.1	47.9	27.4	68.5

4.4 Renewable energy potential

In their 2014 Energy Snapshot [110], the National Renewable Energy Laboratory gives an overview of the different renewable energy sources and their potential for Aruba, this is presented in figure 4.12. It can be seen that both wind and solar power have high potential, but the potential for the other sources is mostly categorised as low. As a results of this, both the NREL as well as the Carbon War Room [112] indicate that *"Aruba will depend heavily on variable wind and solar to reach its renewable energy goals."*

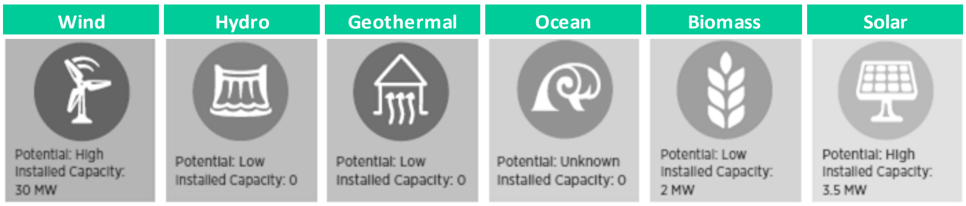


Figure 4.12 Overview of various renewable energy sources and their potential for Aruba [110].

Although the potential of both sources is undeniable, WEB Aruba does not completely share this vision for implementation. According to their calculations the realistic limit of intermittent renewable energy integration in the short-term is in the range of 40-60%. They indicate that in order to cover the remaining share, they will not rely on variable solar and wind energy due to system reliability issues [120]. In the following sections, the potential for each of these resources is explained in more detail. In general, the potential of each source is based on multiple year estimates. However, in relation to the demand data provided for the year 2015, data about the various resources will also be presented for the year 2015.

Ocean energy

These resources include wave, tidal, ocean thermal, salinity gradient and aquatic biomass energy. Although clustered as one, the ocean energy resources are very different in nature, both intermittent (wave, tidal) as well as able to supply base load power (ocean thermal, salinity gradient and aquatic biomass). The potential for these resources therefore varies per resource.

In the case of Aruba, there are little to no fresh water streams [110], this means that there is negligible potential for exploitation of salinity gradient as renewable resource. Wave and tidal energy sources can be found around the island, but potentials are moderate for wave [133], and low for tidal [134]. There is potential for growing aquatic biomass such as algae to produce biofuels, but no study has been found that gives a clear estimate. Therefore, in this thesis, these resources are not specifically considered. The island does however possess potential for the use of ocean thermal resources to produce electricity. This is done by making use of a difference in ocean water temperatures, mostly a result of a thermocline (a distinct temperature difference in surface and deep water ocean layers). This can be found in many tropical regions. This temperature difference can be exploited by means of Ocean Thermal Energy Conversion (OTEC) technology. This involves pumping up deep cold ocean water and exchanging heat with warmer surface water, this drives a Rankine power cycle to produce electricity. The technology is considered viable in areas where the year-round temperature differential is at least 20 degrees Celsius [135].

Biomass / Waste

Due to its dense population, arid ground and dry climate Aruba lacks good biomass resources [112]. The potential for biomass as stated by the NREL factually concerns the use of waste to produce electricity. This can be done directly by incineration to produce steam or indirectly by implementation of a pyrolysis based waste-to-gas plant. This gas can subsequently be used in a dedicated gas turbine, reciprocating engine or boiler. Before it can be converted to energy, the waste needs to be segregated, collected, transported, and, if necessary, pre-treated and/or stored. The potential for this resource is estimated at 10-15 MW [111,136]. This is based on an average production of 400-550 ton of Municipal Solid Waste (MSW) per day [111].

Wind energy

Aruba is blessed with an extraordinary wind resource, due to its constant trade winds blowing steadily from the east. Average wind speeds per month are given in figure 4.13 for 2015. The hourly average wind speeds for two months in 2015 are depicted in figure 4.14. This is based on data provided by [140], the US National Climate Data Centre. The figures demonstrate that wind speeds are relatively constant, both throughout the year and throughout the month, at an average of 8.5 m/s. A cyclical trend can be identified in the year with increased averages around May and June and lower wind speeds around January-February and October-November.

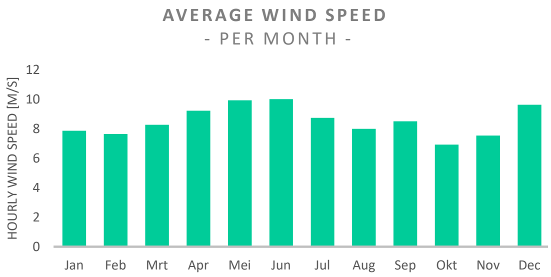


Figure 4.13 Monthly average wind speeds in 2015 [140].

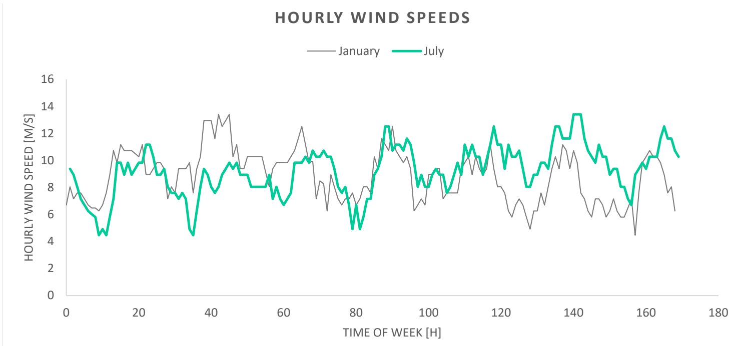


Figure 4.13 Hourly average wind speeds for January and July in 2015 [140].

However, the period of 2014-2015 has been relatively windy. If a multiple year estimate for the wind resource is taken, it is found to be slightly lower at about 7.6 m/s. This corresponds to [107] where the wind resource is estimated at 5000 hours full-load capacity per year. As data for the year 2015 is used as input for the model, this notion is taken into account in section 5.3 on data acquisition.

Finally, figure 4.14 depicts the average hourly wind speed direction. From this image it can be concluded that the dominant wind direction is east at roughly 80 degrees. The vane at 270 degrees indicates the percentage of times of variable wind direction (code 990), indicating that the standard deviation is larger than 30 degrees [138].

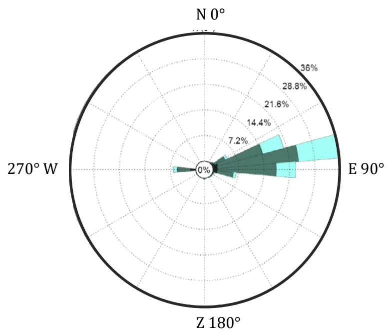


Figure 4.14 Average hourly wind speed direction in 2015 [140].

Solar energy

Due to its favourable climate and its proximity to the Equator, Aruba experiences a constant influx of solar energy, with little influence of seasons. This is depicted in figure 4.15. Hourly irradiation figures are presented in figure 4.16 [137]. Software programme Meteonorm is used as data source for the availability of solar irradiation on Aruba. This provides a dataset of hourly values calculated for a typical year[5]. A complete overview of monthly irradiation and daily global radiation produced for Aruba is given in appendix 1.

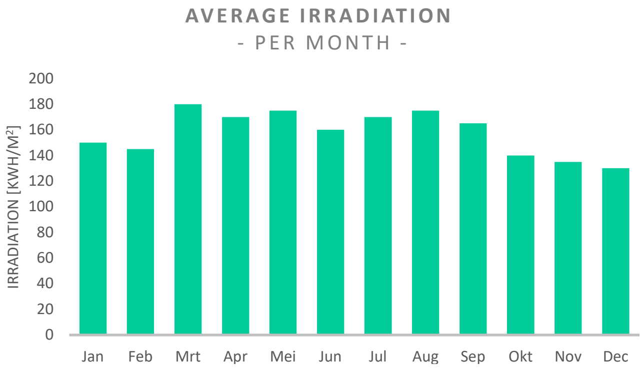


Figure 4.15 Average monthly solar irradiation [137].

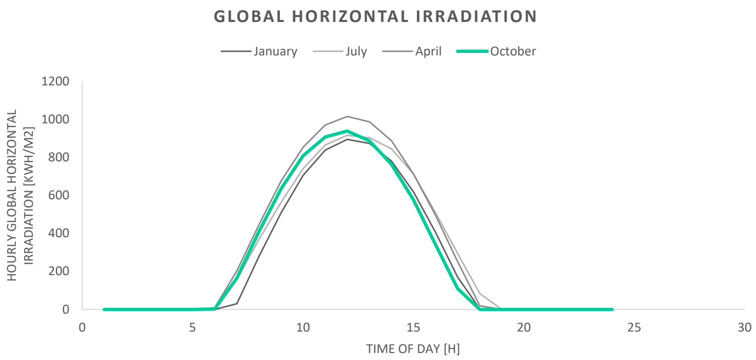


Figure 4.16 Average hourly irradiation for a single day in January, April, July and October [137].

Hydropower

The potential for hydropower on the island is low [110]. Aruba does not possess any significant potential hydropower sites because of its arid topology and geography. Therefore, in this thesis, this resource is not considered.

Geothermal energy

The geothermal potential is stated as low in figure 4.12. This is due to its geographical location, far away from the geothermally active arc roughly stretching north to south from Saba and St. Kitts until St. Vincent and Grenada [131]. It should be added that the potential for geothermal energy is low, within the constraints of current technologies. In the future this may change when single well enhanced geothermal systems (SWEGS) can be deployed to extract heat from rocks deep in the ground and converting it into power using a closed-loop system [112]. Due to lack of detailed research and tests, there is a high level of uncertainty regarding this resource [132]. Therefore, in this thesis, this resource is not considered.

[5] The results are stochastically generated typical years from interpolated long term monthly means. As such, the results do not represent a real historic year but a hypothetical year which statistically represents a typical year at the selected location.

4.5 Transition phases

Based on the potentials of renewable energy sources given in the previous section, the Carbon War Room (CWR) has derived a transition strategy consisting of four phases towards the goal of 100% renewable energy [112]. As stated before, this includes solely the use of electricity, not energy used for transportation, cooking and heating. Their conclusions are based on simulations run using a HOMER [139] model of the Aruban power system. The calculated required implementation of new renewable energy production and storage in phase 1-4 are summarised in table 4.6a to 4.6e. Since WEB Aruba has a different strategy regarding the implementation of renewable energy sources, their scenario of 50% renewable power and 50% gas based power in 2020 is added as Phase 2b, depicted in table 4.6c. In addition, the estimation or calculation of the renewable energy penetration percentage for phase 1, differs between the CWR and WEB Aruba. The former indicates 12%, whereas the latter indicates 19%. In table 4.6a, the original value such as provided by the CWR is depicted.

In terms of energy storage options, both for the short as for the long timescale, it is concluded that large-scale implementation of battery technology does not cost-effectively meet Aruba's unique needs [107]. Therefore, investments have been made in a flywheel storage system and a yet unproven method: underwater compressed air storage. The former deals with fluctuations on a short timescale and the latter is capable of receiving or supplying balancing power for a longer time. Combined with clean power from the planned Urirama wind park, these storage systems will enable Aruba to reduce wind energy curtailment to below 2 percent [107]. These storage options will not be explicitly modelled in this thesis.

Phase 1: Low Renewable Penetration = 12%

Table 4.6a Overview of installed renewable energy in transition phase 1 as defined by [112].

Source	Amount	Description
Wind	30 MW	Vader Piet
Solar	3.5 MW	Airport
Total	33.5 MW	

Phase 2: Medium Renewable Penetration = 30%

Table 4.6b Overview of installed renewable energy in transition phase 2 as defined by [112].

Source	Amount extra	
Wind	24 MW	Urirama
Solar	6 MW	Residential and commercial
WTE	5 MW	
Sum RE Phase 1	34 MW	
Total	69 MW	
Flywheel	15 MW	
Flow batteries	6 MW (10 MWh)	

Phase 2b (WEB): Medium Renewable Penetration = 50%

Table 4.6c Overview of installed renewable energy in transition phase 2b as defined by WEB Aruba.

Source	Amount extra	(Compared to Phase 1)
Wind	24 MW	Urirama
Solar	6 MW	Residential and commercial
WTE	10 MW	
Sum RE Phase 1	34 MW	
Total	74 MW	
Flywheel	15 MW	
Hydrostor	1 MW (8 MWh)	Underwater Compressed Air Storage
Batteries	5 MW (5 MWh)	

Phase 3: High Renewable Penetration = 80%

Table 4.6d Overview of installed renewable energy in transition phase 3 as defined by [112].

Source	Amount extra	
Wind on-shore	30 MW	
Wind off-shore	50 MW	
Solar	180 MW	For 7 m^2/kW = 1.26 km^2 (0.7% of total land area)
WTE	5 MW	
Sum RE Phase 2	69 MW	
Total	334 MW	
Storage	160 MWh	
Sum storage Phase 2	10 MWh	
Storage total	171 MWh	

Phase 4: 100% Fossil Fuel-Free Energy

Table 4.6e Overview of installed renewable energy in transition phase 4 as defined by [112].

Source	Amount extra	
'Firm' RES	26 MW	OTEC, deep SWEGS geothermal, wind-to-hydrogen, algae biofuel
Sum RE Phase 3	334 MW	
Total	360 MW	
Storage	29 MWh	
Sum storage Phase 3	171 MWh	
Storage total	200 MWh	

5. MODEL

5. MODEL

In this chapter the model used in this thesis will be discussed. It will give an explanation for the used modelling approach and will outline choices made in this process. A model is an approximate representation of reality. In the case of a mathematical model, it can be fully described by equations and assumptions. These indicate relations between variables and constraints of variables within the model. Therefore, this chapter will outline and explain the model of the power system of Aruba and the assumptions made. A separate chapter (6. Optimisation) is devoted to the modelling of the optimisation strategy.

5.1 General characteristics

The following general characteristics govern the behaviour of the model and are therefore summarised here. The model is deterministic, this means that all predications of supply and demand are provided: there is no uncertainty. The model performs simulations with a one-hour time step resolution. For computational speed the model is for 500 EVs and the month July. This month reflects the year well as its demand, wind speeds and solar radiation approximate the yearly average. The effects are scaled up to represent 50,000 EVs for a whole year.

The model used in this thesis consists of the following power system components and power demands, which together represent the power system of Aruba. These are depicted in figure 5.1. Conventional power generation units run on gas as fuel. It is therefore assumed that the strategy as formulated by WEB in phase 2b in section 4.5, will be implemented in the simulated scenarios. In table 5.1 the power generation components are summarised.

Table 5.1 Overview of modelled power system components and their respective minimum and maximum values.

Power system component		**Min**	**Max**
Steam power generation	$P_{steam,t}$	15 MW	60 MW
- *Steam turbine unit*	$P_{steam,j,t}$	15 MW	30 MW
- *Number of online units*	J_t	*1*	*2*
Reciprocating power generation	$P_{recip,t}$	0 MW	45 MW
- *Recip power unit*	$P_{recip,k,t}$	2 MW	11.25 MW
- *Number of online units*	K_t	*0*	*4*
Peak power generation	$P_{peak,t}$	0 MW	47 MW
- *Peak power unit*	$P_{peak,l,t}$	1 MW	7.8 MW
- *Number of online units*	L_t	*0*	*6*

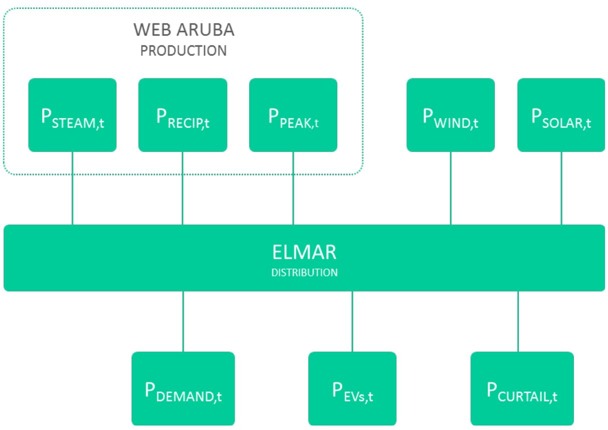


Figure 5.1 Model of Aruban power system with different power components.

Model variables and parameters

The variables used in the model and in the equations that follow in this chapter are summarised here:

t	: time step
T	: the number of time intervals
j	: the steam turbine unit number
k	: the reciprocating engine unit number
l	: the peak engine unit number
J_t	: the number of steam units online at time step t
J^{min}	: the minimum number of steam units online
J^{max}	: the maximum number of steam units online
K_t	: the number of recip units online at time step t
K^{min}	: the minimum number of recip units online
K^{max}	: the maximum number of recip units online
L_t	: the number of peak units online at time step t
L^{min}	: the minimum number of peak units online
L^{max}	: the maximum number of steam units online
$P_{steam,j,t}$	: the output power of steam unit j at time step t
$P_{steam,t}$	: the combined output power of all steam units at time step t
$P_{steam,j}{}^{min}$	: the minimum output power of steam unit j
$P_{steam,j}{}^{max}$	: the maximum output power of steam unit j
$P_{recip,k,t}$	: the output power of recip unit k at time step t
$P_{recip,t}$	: the combined output power of all recip units at time step t
$P_{recip,k}{}^{min}$	: the minimum output power of recip unit k
$P_{recip,k}{}^{max}$	: the maximum output power of recip unit k
$P_{peak,l,t}$	: the output power of peak unit l at time step t
$P_{peak,t}$	: the combined output power of all peak units at time step t
$P_{peak,l}{}^{min}$	: the minimum output power of peak unit l
$P_{peak,l}{}^{max}$	: the maximum output power of peak unit l
$P_{spinning}{}^{min}$	: the minimum spinning reserve
$P_{spinning,t}$	: the spinning reserve at time step t
$P_{demand,t}$	: the power demand at time step t
$Q_{demand,t}$	: the residual demand at time step t
$P_{curtail,t}$	: the curtailed power at time step t
$P_{solar,t}$	: the solar power production at time step t
$P_{wind,t}$	: the wind power production at time step t

Other modelling choices and assumptions will be explained in more detail in the following sections.

5.2 Conventional power generation modelling

Steam power generation

This power generation component represents steam turbine generation or otherwise referred to as thermal power production (TPP). This consists of two steam turbines in combination with two boilers. The minimum power output for each steam unit is 15 MW, and their maximum power output is 30 MW. These are the boiler operating constraints, not the turbines [117]. Their combined power output is given by $P_{steam,t}$. Unit 1 is always online and operates in isochronous (frequency) mode and sets the grid frequency. Unit 2 is operated in droop mode and produces constant power output. In case residual demand is very low or even less than zero, unit 2 may be switched off. The number of steam units online is given by the value J_t. In the current (2015) situation of 20% renewable power penetration, these generators take up 30% of the yearly demand.

$$\mathrm{j} = [1, 2] \tag{5-1}$$

$$J^{min} = 1 \tag{5-2}$$

$$J^{max} = 2 \tag{5-3}$$

$$J^{min} \leq \mathrm{J_t} \leq J^{max} \tag{5-4}$$

$$P_{steam,j}{}^{min} = 15\ MW \qquad \forall j \tag{5-5}$$

$$P_{steam,j}{}^{max} = 30\ MW \qquad \forall j \tag{5-6}$$

$$P_{steam,j}{}^{min} \leq P_{steam,j,t} \leq P_{steam,j}{}^{max} \qquad \forall j,t \tag{5-7}$$

$$P_{steam,t} = \sum_{j=J_{min}}^{J_t} P_{steam,j,t} \quad \forall t \tag{5-8}$$

Recip power generation

This power generation components represents a group of the four larger and newer, more efficient reciprocating engines that are operated near-continuously in the current situation. Their combined power output is given by $P_{recip,t}$. These units are switched on and off to remain sufficient spinning reserve. The number of recip units online is given by the value K_t. When online, these are operated in droop mode, so their power output is constant. Conversely to the steam turbines, these units have a much lower minimum output power. The minimum power output for each recip unit is 2 MW and their maximum power output is 11.25 MW. This is only true for the case of a 'clean' fuel such as diesel or gas, not with the current HFO fuel, for which a much higher minimum would be the case. In the current (2015) situation of 20% renewable power penetration, these generators take up 30% of the yearly demand.

$$\mathrm{k} = [1, 2, 3, 4] \tag{5-9}$$

$$K^{min} = 0 \tag{5-10}$$

$$K^{max} = 4 \tag{5-11}$$

$$K^{min} \leq \mathrm{K_t} \leq K^{max} \tag{5-12}$$

$$P_{recip,k}{}^{min} = 2\ MW \qquad \forall k \tag{5-13}$$

$$P_{recip,k}{}^{max} = 11.25\ MW \qquad \forall k \tag{5-14}$$

$$P_{recip,k}{}^{min} \leq P_{recip,k,t} \leq P_{recip,k}{}^{max} \qquad \forall k,t \tag{5-15}$$

$$P_{recip,t} = \sum_{k=K_{min}}^{K_t} P_{recip,k,t} \quad \forall t \tag{5-16}$$

Peak power generation

This power generation components represents a group of the six smaller and older, less efficient reciprocating engines that are operated to cover peak demand. Their combined power output is given by $P_{peak,t}$. These units are purposely modelled separately from the other four reciprocating engines, since these are only used for peak power production. In case of large residual demand, these units are switched on and off to remain sufficient spinning reserve. In nature these are the same type of engines as the recip power generation and thus their characteristics are the same. The number of peak units online is given by the value L_t. When online, these are operated in droop mode, so their power output is constant. The minimum power output for each peak unit is 1 MW and their maximum power output is 7.8 MW. Again, this is only true for the case of a 'clean' fuel such as diesel or gas, not for HFO fuel. In the current (2015) situation of 20% renewable power penetration, these generators take up 20% of the yearly demand.

$$\mathrm{l} = [1, 2, 3, 4, 5, 6] \tag{5-17}$$

$$L^{min} = 0 \tag{5-18}$$

$$L^{max} = 6 \tag{5-19}$$

$$L^{min} \leq \mathrm{L_t} \leq L^{max} \tag{5-20}$$

$$P_{peak,l}{}^{min} = 1\,MW \qquad \forall l \tag{5-21}$$

$$P_{peak,l}{}^{max} = 7.8\,MW \qquad \forall l \tag{5-22}$$

$$P_{peak,l}{}^{min} \leq P_{peak,l,t} \leq P_{peak,l}{}^{max} \qquad \forall l,t \tag{5-23}$$

$$P_{peak,t} = \sum_{l=L_{min}}^{L_t} P_{peak,l,t} \qquad \forall t \tag{5-24}$$

Power dispatch

In principle, during each time step, the residual demand should be satisfied by the combined production of fossil-fuel based sources, according to:

$$\sum_{j=J_{min}}^{J_t} P_{steam,j,t} + \sum_{k=K_{min}}^{K_t} P_{recip,k,t} + \sum_{l=L_{min}}^{L_t} P_{peak,l,t} \geq Q_{demand,t} \qquad \forall t \tag{5-25}$$

The dispatch of power from each source is governed as depicted by the flow chart in appendix 4a and the thereto coupled equations in appendix 4b. This is mainly based on the implementation of spinning reserves. These will be discussed on the next page. Dispatch is performed according to the following merit order: steam- recip- peak. This is based on the fact that steam turbine unit 1 is continuously operated in isochronous mode and steam turbine generation is preferred over reciprocating generation due to its higher inertia and therefore larger capability to remain network stability. Reciprocating power production is second in line as this represents the larger and more efficient reciproating engines, and are followed by peak power generation.

The power production of the units that operate in droop mode is modelled to depend on a here defined load factor $f_{load,t}$, stated in eq. 5-26, which depends on the type and amount of units that are online, the minimum spinning reserve and minimum steam power production. This load factor is then used to divide power over the online units. Albeit that steam turbine generation is preferred over reciprocating generation and peak power in the order of dispatch due to its higher inertia, the amount of power production from reciprocating and peak power is preferred to be larger due to their higher efficiency. Therefore in these calculations, a bias factor is used to ensure a larger production from the reciprocating power production and peak power production compared to steam turbine unit 2, and an otherwise equal division based on the load factor.

$$f_{load,t} = \frac{P_{steam,j}{}^{max} + K_t * P_{recip,k}{}^{max} + L_t * P_{peak,l}{}^{max} - P_{spinning,t}{}^{min} - J_t * P_{steam,j}{}^{min}}{P_{steam,j}{}^{max} + K_t * P_{recip,k}{}^{max} + L_t * P_{peak,l}{}^{max}} \tag{5-26}$$

In this thesis, the aim is to see the influence of EVs on the residual demand, the amount of power generation that is needed from fossil fuel based generators. In principle, residual demand is calculated by subtracting the available renewable power from the power demand. This reflects a merit order in which renewable sources are preferred over conventional production source. Thus residual demand $Q_{demand,t}$ can be calculated using:

$$Q_{demand,t} = P_{demand,t} - P_{solar,t} - P_{wind,t} \qquad \forall t \tag{5-27}$$

A surplus of renewable energy is thus represented by a negative residual demand, which means if no storage is implemented, renewable energy is spilled. A positive residual demand is the amount of power that needs to be covered by conventional fossil fuel based generation.

Reserves

Non-event reserves in the form of regulating reserves (to keep the frequency within its normal bandwidth) are assumed to be performed by isochronous operation of steam unit 1. Thus by the governor response of the steam turbine to the change in demand. Non-event reserves in the form of following reserves to cover predicted imbalances in load and supply of renewables are performed by steam unit 2, reciprocating and peak power generation.

Since a deterministic model is used, contingency event reserves in the form of instantaneous events are not modelled. However, we are interested in the effect of demand response through controlled EV charging on spinning reserves. These are secondary event reserves that cover non-instantaneous imbalances due to a large drop in renewable power production and instantaneous imbalances, such as due to a loss of one generator. The amount of spinning reserve at each time step $P_{spinning,t}$ can be calculated using eq. 5-28. Using this equation, the values for J_t, K_t and L_t are increased by the dispatch algorithm, emulating the operation that units are switched on and off to ensure that the spinning reserve at each time step exceeds the minimum spinning reserve requirement.

$$P_{spinning,t} = J_t * P_{steam,j}{}^{max} + K_t * P_{recip,k}{}^{max} + L_t * P_{peak,l}{}^{max} - Q_{demand,t} \qquad \forall t \tag{5-28}$$

The minimum required spinning reserve constraint $P_{spinning}{}^{min}$ is assumed to be 25 MW. This is a pragmatic way to retain constant spinning reserve. During every moment of operation, i.e. for every time step, the amount of spinning reserve needs to exceed this reserve requirement:

$$P_{spinning}{}^{min} = 25\,MW \qquad \forall t \tag{5-29}$$

$$P_{spinning,t} \geq P_{spinning}{}^{min} \quad \forall t \tag{5-30}$$

Primary contingency reserves are assumed to be covered by the governor response of the isochronous operation of steam unit 1 reserves. And finally, tertiary reserves, or back-up power supply, in the case of Aruba is covered by the separate single diesel generator of 20 MW. Normally, this unit is offline, but ready to start up in less than 15 min. Tertiary reserves are not explicitly modelled.

Electricity demand & EV demand

The electricity demand $P_{demand,t}$ is a given input to the model, based on the demand data. The electricity demand from EVs $P_{EVs,t}$ is modelled as an exogenous demand next to the original electricity demand. Its value is based on the number of EVs on the road, the implemented charging infrastructure and the control scenario.

Curtailed power

At moments when there is too much renewable power this is curtailed as $P_{curtail,t}$. However, it cannot be said exactly from which source this curtailed power originates. It will be a share of the aggregate of online power production from both renewable and conventional generation.

Overview of assumptions:

- Deterministic: no uncertainty.
- One-hour time step resolution.
- Conventional dispatch order is: steam - recip - peak, based on generator inertia.
- Power from Recip and Peak engines is enlarged with a bias factor because of their higher efficiency.
- 2 boilers are online, and thus are steam turbine limits 15 and 30 MW respectively.
- Conventional generator fuel is a clean (gas) fuel, so low minimum output values apply.
- Constant spinning reserve requirement of 25 MW.
- Units are dispatched in normal dispatch order to remain sufficient spinning reserve.

5.3 Data acquisition

One year data series are used with a one-hour time step resolution. For wind and solar power production (of which the latter is modelled to be dependent on temperature) data series of two separate sources are used. Data sets are collected for the year 2015.

Meteonorm [137] provides climatological data for a wide variety of geographical regions around the globe, including temperature, wind speeds and irradiation data. This data source is widely used for solar engineering applications. The data used is global horizontal irradiation given in 1-hour resolution. This is stochastically generated interpolated data based on measurements for multiple years at multiple locations and constructed to represent a 'typical year'. *"As such the results do not represent a real historic year but a hypothetical year which statistically represents a typical year at the selected location." [137].*

The National Climatic Data Center (NCDC) as part of the US National Oceanic and Atmospheric Administration (NOAA) provides wind and temperature data for the model (NCDC, 2015). This includes global hourly and synoptic observations and are compiled in an Integrated Surface Database (ISD). A comparison was made between the real wind data and the wind data synthesised by Meteonorm, and it was found that the synthesised data did not adequately reflect the variability of the wind speeds evident in the real data. Consequently, the decision was made to use the real measured data for the wind speeds and temperature, complemented with the solar irradiance data from Meteonorm. For the case of Aruba a two-piece 2015 dataset is downloaded[6] for the location of the Reina Beatrix International Airport. These pieces are combined at June 1, 2015. The data used are average hourly wind speeds and average hourly temperatures. To account for the fact that 2015 was a windy year (average 8.5 m/s), a correction factor of 0.9 is used here to reduce it to a multi-year estimate with an average of 7.6 m/s.

$$I_{solar} = f(t) \tag{5-31}$$

$$U_{wind} = 0.9 * f(t) \tag{5-32}$$

$$T_{air} = f(t) \tag{5-33}$$

Demand data for 2015 is provided by WEB Aruba. The demand is assumed to retain this value in the future due to counteracting effects of population and GDP growth versus energy efficiency improvements.

$$P_{demand} = f(t) \tag{5-34}$$

These datasets and their characteristics have been outlined in chapter 4 and will therefore not be discussed in more detail here.

[6] Data order on 20/9/2016.

5.4 Renewable power generation modelling

Wind and solar power are modelled as intermittent renewable energy sources. Their production depends on the wind speed, temperature and solar irradiation data. The wind power production is given by $P_{wind,t}$ and the solar power production by $P_{solar,t}$.

Solar power

A simple model is used to calculate the produced solar power based on an installed number of solar panels, solar irradiation data and ambient air temperature. In different transition phases where the capacity of solar power production is expanded, the number of panels, or modules, is simply expanded. This is based on identical modules of 250 W peak power. The conversion of irradiation data to solar PV generation is calculated according to eq. 5-35 – eq. 5-47. The total produced solar power generation is:

$$P_{solar}(t) = A_{module} * I_{solar}(t) * N_{modules} * \eta_{solar}(t) \tag{5-35}$$

Of which A_{module} is the peak power per module, $N_{modules}$ is the amount of PV modules installed, both constants. Conversely, η_{solar} is variable and represents the total combined efficiency according to:

$$\eta_{solar}(t) = \eta_{module}(t) * \eta_{DClosses} * \eta_{inverter} * \eta_{transformer.solar} \tag{5-36}$$

Of which $\eta_{DClosses}$, $\eta_{inverter}$ and $\eta_{transformer,solar}$ are assumed constant values. η_{module} is the efficiency of the solar panel, which depends on the cell temperature T_{cell} according to eq. 5-37 [142].

$$\eta_{module}(t) = \eta_{Tref} * \left(1 - \beta_{ref} * \left(T_{cell}(t) - T_{ref}\right)\right) \tag{5-37}$$

In which T_{cell} is calculated using eq. 5-38 [143,144]:

$$T_{cell}(t) = T_{air}(t) + \left(\frac{T_{NOCT} - T_{ref}}{I_{ref}}\right) * I_{solar}(t) \tag{5-38}$$

In these calculations, η_{Tref} is assumed to be a lifetime average of 18% for crystalline silicon (mono-Si) [146]. This is chosen to represent an average over the lifetime of the cell. β_{ref} is the temperature coefficient. A value of 0.0041 is taken [145]. T_{ref} and T_{NOCT} are constants of 25°C and 45°C, respectively. T_{air} is the ambient air temperature as function of t. I_{ref} is the reference value of solar irradiation, with a value of 800 W/m2 [143]. Efficiency values are assumed 0.93 for DC losses [147], 0.95 for inverter losses [148] and 0.98 for transformer efficiency [149].

The used constants in the calculation of solar power are given here:

$$A_{module} = 1.67\ m^2 \tag{5-39}$$

$$\eta_{Tref} = 0.18 \tag{5-40}$$

$$\beta_{ref} = 0.0041 \tag{5-41}$$

$$T_{ref} = 25\ °\mathrm{C} \tag{5-42}$$

$$T_{NOCT} = 45\ °\mathrm{C} \tag{5-43}$$

$$I_{ref} = 800\ W/m2 \tag{5-44}$$

$$\eta_{DClosses} = 0.93 \tag{5-45}$$

$$\eta_{inverter} = 0.95 \tag{5-46}$$

$$\eta_{transformer.solar} = 0.98 \tag{5-47}$$

Wind power

In the case of wind power, again a simple model is used to calculate the produced wind power based on an installed number of turbines and wind speed data. In different transition phases where the capacity of wind power production is expanded, the number of turbines is simply expanded. This is based on identical Vestas V90 turbines of 3 MW peak power. The conversion of these wind speeds to wind turbine generation $P_{wind,t}$ can be calculated according to eq. 5-48– eq. 5-56. The total produced wind generation is:

$$P_{turbine}\ (t) = P_{turbine}\ (t) * \eta_{turbine}\ * \ \eta_{transformer.wind} \tag{5-48}$$

Of which $N_{turbine}$ is the amount of wind turbines installed, $\eta_{transformer,wind}$ is the assumed transformer efficiency, both constants. $P_{turbine}$ is the power produced per turbine as a function of wind speed at hub height U_{hub}, according to:

$$P_{turbine}\ (t) = f\big(U_{hub}\,(t)\big) \tag{5-49}$$

This relation is depicted in figure 5.2. In this graph [150] the nominal power and cut-in and cut-off wind speeds of 4 and 24 m/s, respectively, are clearly visible.

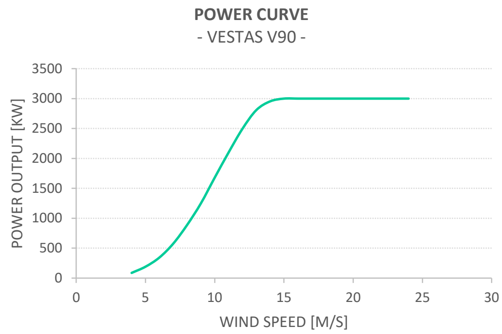


Figure 5.2 Vestas V90 3MW power curve, used for conversion of wind speeds to turbine power output [150].

The average hourly wind speeds U_{wind} are translated to the wind speeds at representative hub height of the turbine. This translation makes wind speeds approximately 16% higher than at the height of measurement. This conversion is calculated through eq. 5-50 [151], in which z_{hub} is hub height, z_{ref} is height of wind speeds measurement and z_0 is the roughness parameter.

$$U_{hub}\,(t) = U_{wind}\,(t) * \frac{ln\left(\frac{z_{hub}}{z_0}\right)}{ln\left(\frac{z_{ref}}{z_0}\right)} \tag{5-50}$$

In the case of Aruba, this means roughly a hub height of 80 meter [150], assuming the base of the turbine is at sea level. The wind speed measurements taken at the airport meteorological station are at 18.3 meter from sea level [140]. The surface roughness parameter (or roughness length) is taken as 0.001 m for a *blown sea* condition [152]. The is chosen since Aruba has its trade winds coming directly from the Carribean Sea. Lastly, wind power transformer effiency is assumed to be 0.95 [153].

The used constants in the calculation of wind power are given here:

$$\eta_{transformer\ .wind}\ =\ 0.95 \tag{5-51}$$

$$z_{hub}\ =\ 80\ m \tag{5-52}$$

$$z_{ref}\ =\ 18.3\ m \tag{5-53}$$

$$z_0\ =\ 0.001\ m \tag{5-54}$$

Model functioning & validation

Many assumptions are made in this model, therefore a comparison is made to provide security that the model is able to provide comparable figures to the real-life situation. As a reference scenario or base case, phase 1 of the energy transition is simulated with the model and compared to data provided by WEB Aruba. This is used to check the functioning and outcomes of the model. This is done bases on two criteria: 1) the shares of power production from each source in the year 2015, and 2) the power dispatch profile based on the power generation of each source.

1) Power production shares

The installed capacities in this phase are 30 MW of wind power and 3.5 MW of solar power. Steam, recip and peak power units are used to cover the remaining demand. Gas plays a negligible role in this transition phase as it only accounts for 0.15% of the yearly demand. The yearly average shares in percentages of generation from different sources for 2015 as provided by WEB and the average shares as outcomes of the model are given in table 5.2 [117].

Table 5.2 Comparison of generation shares provided by WEB and outcomes of the model.

Yearly average [%]	STEAM	RECIP & PEAK	GAS	WIND	SOLAR
WEB	33.3%	46.1%	0.15%	20.5%	0.0%
Model	33.1%	49.7%	0.0%	16.5%	0.67%

If the results from the model are compared to the data provided by WEB, it is clear that overall the generation shares agree well. Steam power generation is approximately the same, reciprocating and peak generation represent a somewhat larger share than indicated by WEB. This is due to the anomaly in the amount of power from renewables. This difference can be explained by the following notions. Firstly, WEB gives only the power production from wind power, since solar power (3.5 MW from the airport) is not produced by WEB and thus not included in these aggregate shares. Secondly, a higher percentage of renewable power as opposed to the timeline presented in figure 4.9 in chapter 4 is presented. A share of 20.5% of wind power, compared to a combined value for wind and solar of 18.9% in 2015 depicted in the timeline. This is due to the fact that in the timeline, also desalination was taken into account. And thirdly, for the average demand of 105 MW for 2015, 20.5% of wind power would lead to a capacity factor of 67%. This is deemed unrealistic and therefore the lower wind share in the model is assumed more acceptable. This leads to a capacity factor of 57%, which is high, but more realistic. It should be noted that this is the capacity factor without down-time. In reality, this thus will even be slightly lower. With these consideration in mind, the power production share of the various production sources corresponds well to the data provided by WEB and the realistic expectations.

2) Power dispatch profile

Based on the information provided by WEB Aruba about the real-life situation, the unit dispatch is incorporated in the model to let each power source contribute to the balance between supply and demand on the one side, and at the same time keep suffient reserves. In the following section the dispatch of each power source for two days is presented and compared to the provided information.

In figure 5.3, the power dispatch is depicted for day #102 and #112 in the year 2015, i.e. in transition phase 1. In figure 5.4, directly beneath figure 5.3, the real dispatch data from as presented in chapter 4 are depicted once more. First of all, it can be seen that both steam and reciprocating power generation provide base load power and peak power is dispatched on moments when demand as high. Furthermore, steam power generation reacts to changes in variable wind and solar power production, as well as peak power production.

Since the model simulates in 1-hour time steps, obviously there is only variation between the different time steps and not the short term variations as shown for the real data.

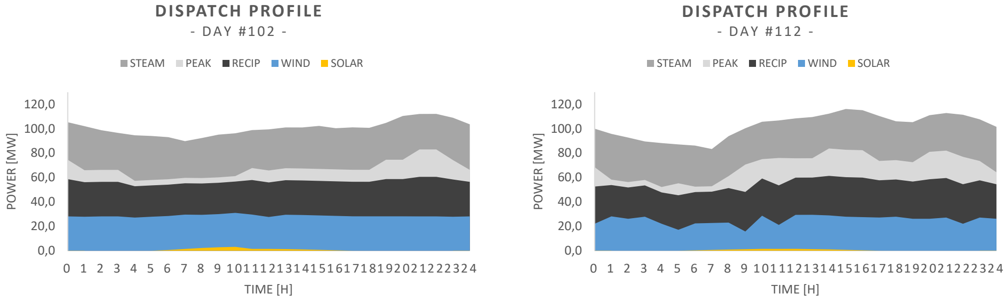


Figure 5.3 Dispatch profile output from model for a single day with stable wind generation (a) and for a day with varying wind generation (b).

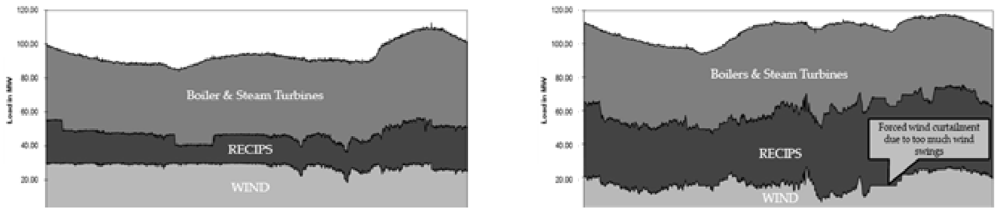


Figure 5.4 Dispatch profile data from WEB for a single day with stable wind generation (a) and for a day with varying wind generation (b).

Now two days are analysed in a 50% renewable energy penetration scenario with dominant solar power installed, the dispatch changes as follow and is depicted in figure 5.5. What can be seen is that as the production of solar power increases, reciprocating power is reduced and at midday peak is even reduced to zero. Peak power production is solely used during the evening peak when demand goes up and solar, power is not present. Lastly, steam power production is continuously used during both days, but is significantly reduced during midday until the 15 MW minimum for unit #1 is reached. For both days it is clear that during midday total power production exceeds demand. This results in the curtailment or spillage of large amounts of power for day #102 and to a small extent for day #112.

Thus, steam turbine generation provides continuous base load power and adapts to variable renewable energy production and changes in the dispatch of reciprocating and peak power production. Both reciprocating power and peak power adapt to renewable power production and are switched on and off to remain sufficient spinning reserve capacity. This corresponds well to the real role division of the different power sources. Moreover, the assumed constant spinning reserve requirement of 25 MW seems to give the right dispatch profile and production shares.

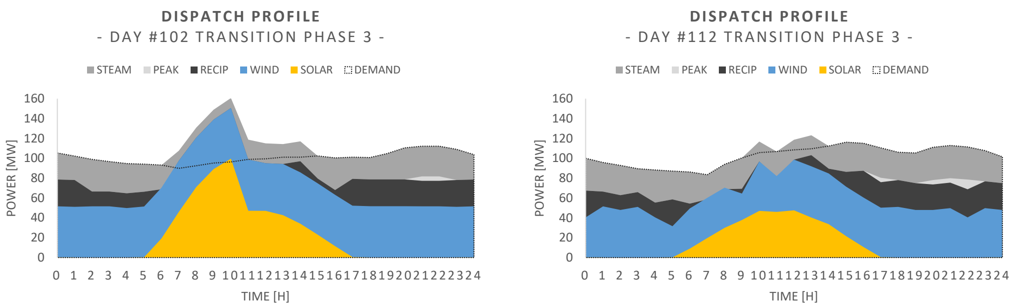


Figure 5.5 Dispatch profile output for two days in a dominant solar scenario with 50% renewable penetration.

In conclusion, the shares of power from fossil-fuel based generation and renewable generation are in good agreement with the real situation and dispatch of the different power generation units is performed similarly to the role division and merit order in the real life situation. Based on these insights, the functioning of the model and the assumptions made are deemed appropriate.

5.5 Price signal

This section explains how residual demand influences the time and magnitude of EV charging.

A dynamic electricity price signal is constructed based on the magnitude of the residual demand. This is modelled to work as a theoretical incentive for EV owners or smart EV charge equipment to decide when to charge. Obviously, there are multiple ways to achieve this connection between EV charging and the operation of the power system under the influence of renewable energy sources. In this thesis the choice has been made to use a price signal as a pragmatic and direct way of achieving this connection, since it reflects one of the strongest incentives to influence behaviour. This choice for a price incentive entails that the optimisation used in this thesis is based on cost of charging. Another form could be to maximize the usage of renewable energy. Other options to establish the connection between EV charging and the operation of the power system will be discussed in section 8.3.

Objectives

EVs as flexible loads are able to provide value to the power system by shifting the time and power with which they are charged. As a first step, making sure EVs are charged during times of low demand instead of during peak hours can solve a possible emerging problem for future power systems. This uncontrolled and simultaneous charging would otherwise lead to a need for a significant increase of installed capacity and high peak power production costs [49]. Therefore, shifting the charge moment to avoid creating these peaks is a first objective.

Another important objective is to reduce the possible curtailment of renewable energy sources. In places where a large penetration of renewable power sources is envisioned, significant overcapacity will be built as this is the cheapest option to satisfy demand with renewables [141]. This will lead to a surplus of power production, for example during midday in the case of solar power. Therefore, a second objective is to increase the electricity demand during times of high renewable energy production to reduce curtailment.

The third and last objective deals with smoothing valleys and peaks of the residual demand profile. This is an extension of the second objective. It entails introducing extra EV demand during times of much renewable production to not just reduce curtailment but effectively fill up a valley in residual demand. Furthermore, sharp peaks of dispatchable power production as a result of sudden drops (intermittency) of renewable production can be reduced by feeding electricity back into the grid. This replaces the role of conventional power generation and is only possible in the case of bi-directional charging. This reduces the curtailment of renewable power that would otherwise be inhibited of entering the grid due to its negative effect on dispatchable generation and grid stability.

The aims of controlled EV charging and discharging as considered in this thesis is to firstly reduce peak power demand due to uncontrolled charging, secondly to reduce the curtailment of renewable energy due to overproduction, and thirdly, reduce curtailment as a result of intermittency. The three aims are summarised here:

1) reduce peak power demand due to uncontrolled charging
2) reduce the curtailment due to overproduction
3) reduce curtailment as a result of intermittency

Method

To achieve these objectives, an electricity price is implemented that reflects peak power demand of dispatchable generation and availability of renewable energy through a dependency on residual demand. A similar approach is followed as used in [102], where the authors found that a real-time price gives the right incentives. This way EV charging is stimulated at times of low residual demand through a low electricity price, and is discouraged in times of high residual demand through a high price.

The residual demand and the price are recalculated every simulation step to include EV charging power demand. This done to represent *price inflation* due to EV demand.

The price as a result of the residual demand reflects the merit order of generation units which presents an increase in marginal costs for an increase in generation demand. In reality, this is a stepwise increase based on the different generator types and characteristics. In this model it is assumed to be a continuous relation. It is modelled to represent the so-called long run marginal cost (LRMC) curve. *"The LRMC of a certain technology consists of both the marginal cost of generation and the capital costs which have to be recovered in the expected number of hours that this generation technology will be dispatched in its lifetime. A back-up diesel generator that is expected to operate only a few hours per year therefore has much larger LRMC, although its short run marginal costs may be similar to other diesel generators. According to micro-economic theory, either in a centrally planned system or a perfect market, so much generation capacity will be built that the LRMC of the next plant would be higher than the value of non-served energy." [102].* A graphical representation of this cost merit order and the resulting LRMC curve for Aruba are depicted in figure 5.6. Note that steam turbine generation has a higher marginal cost compared to reciprocating and peak power generation, but is higher up in the dispatch merit order due to its higher inertia and thus capability of providing grid operation stability.

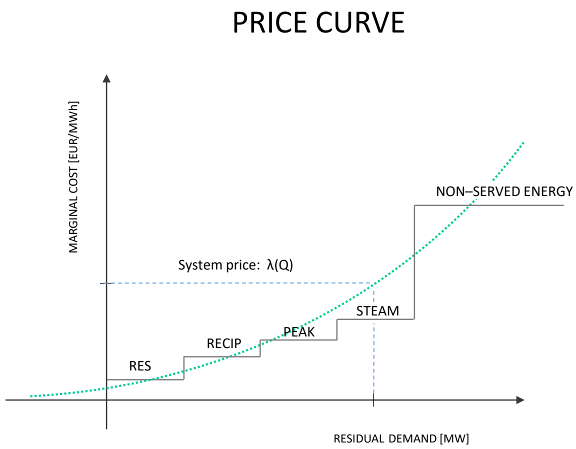


Figure 5.6 Price curve based on LRMC values for different power generation sources.

The price signal λ as a function of residual demand $Q_{demand,t}$ can be calculated using eq. 5-55:

$$\lambda(Q_{demand,t}) = A * 2^{\,B*Q_{demand,t}} \tag{5-55}$$

These constants have been determined using the notion that the yearly average price should be sufficiently high in order to cover the capital cost of renewable energy generation units. It should also reflect the cost of gas based generation and the value of non-served energy. It has been found that the following values work well to reflect these characteristics:

$$A = 35 \;\; EUR/MWh^2 \tag{5-56}$$

$$B = 0.04 \;\; h \tag{5-57}$$

This results in a yearly price average that equals the levelised costs of wind energy production on Aruba and higher values represent the costs of generation from fossil-fuel based generators.

5.6 EV Modelling

Within the system model the EVs are modelled as a simple battery system. The modelling approach, the relations used and the assumptions made are discussed in the following section.

Battery capacity

In this thesis, each EV is assigned a value from a distribution of energy capacity values. The used type of distribution and characteristic are outlined below.

> The energy content or capacity of the modelled electric vehicles depends on the type and the model of car. In the future, electric vehicles will have batteries with a higher energy content than today [154]. It is difficult to predict the actual energy content of the cars that will be on the road. However, the expectance is that most regular light-duty vehicles will have a value around 40-60 kWh, but larger vehicles will have batteries with a higher energy content, in the range of 80-120 kWh. Furthermore, to include the case of pre-owned cars the effect of capacity fading should be taken into account.
>
> The expectation is that the majority of values will be close to the average and only few vehicles will very large capacities. Very low capacities will not be present at all.

Based on the above, the distribution of energy capacity of each EV is modelled using a Weibull distribution, with values approximately between 30 and 120 kWh. An alpha value of 1.5 and a beta value of 30 are taken, leading to an average value of 60 kWh. The resulting distribution is depicted in figure 5.7.

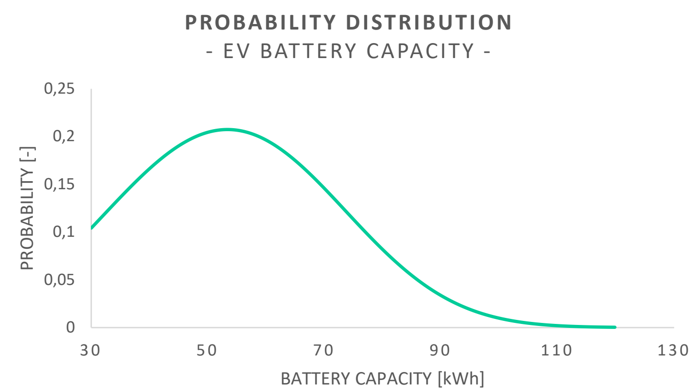


Figure 5.7 Distribution of EV battery capacity values in model.

The estimation of the EV battery capacities is made under the following assumptions:

- EV battery capacity will be higher than is currently normal for EVs;
- Battery capacity will be distributed over EVs according to their daily driving distances.

Driving

In this thesis, EVs are modelled individually. In reality each EV has a specific energy consumption value which depends on e.g. the type of vehicle, weather conditions, driving style, and traffic conditions. In this thesis, each EV is assigned a value from a distribution of energy consumption values. The used type of distribution and characteristic are outlined below.

> In a recent study [155] consumptions values are derived from real driving cycles of a battery electric vehicle (BEV). It was found that the average electricity consumption is in the range of 0.14 kWh/km for small BEVs to 0.19 kWh/km for large BEVs. Furthermore, the consumption depends on the type of use, namely 0.13 kWh/km for driving on roads and nearly 0.20 kWh/km for driving on motorways.
>
> To account for the effect of air-conditioning on the energy consumption, a simple assumption is made where a constant electric load of 2 kW is taken [156]. At an average assumed travelling velocity for Aruba of 40 km/h, this becomes an extra 0.05 kWh/km. In the future, electric vehicles are predicted to become more energy efficient and will thus have a lower consumption value.
>
> The expectation is that the majority of values will be close to the average and only few combinations of driving style, weather conditions, type of vehicle and traffic conditions will lead to very high or very low values.

Based on the above, the distribution of energy usage of each EV is modelled as a normal (Gaussian) distribution, with values approximately between 0.12 and 0.22 kWh/km. An average value of 0.17 kWh/km and a standard deviation of 10% with a value of 0.017 kWh/km are taken. The resulting distribution is depicted in figure 5.8.

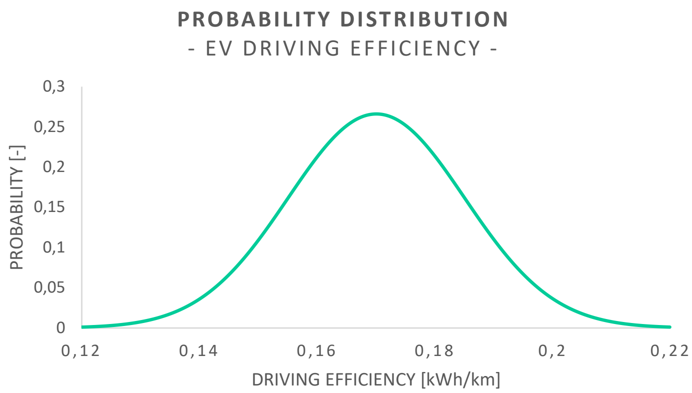


Figure 5.8 Distribution of EV driving efficiency values in model.

The estimation of the energy consumption through driving is made under certain assumptions:

- EV is used only by one individual (i.e. the energy consumption is explained only by the driving pattern of a single individual);
- EV is used for all trips made in the day;
- Same EV is used on all days of the week

The above implies that the EV efficiency is assumed constant for all days in the analysis.

Driving cycles

A Dutch mobility dataset [157] is used as a basis for modelling driving profiles and adapted to the case of Aruba, since such mobility data does not exist for the island. This dataset consists of a total of over 140,000 personal movement information collected through a large survey. In this survey, data is gathered about type of movement, type of vehicle, motivation for movement, etc. This data is collected and compiled with an identification number (ID) for each trip, person and household. Of this set, almost 43,000 movements are made by a driver in a personal car. Motivations for movements within this subset include, among other things: travel to home, to work or work related visit, picking up or bringing people, travel to education, running errands or shopping, sport or hobby and travel for leisure. The main characteristics of this data are presented in appendix 2b.

In this thesis we are interested in driving cycles, thus we are only interested in people that make their daily trips and arrive at home at the end of the day. Single trips are excluded from the data. When solely the data entries for people (personal IDs) that arrive home are taken, this consists of roughly 18,000 entries. However, people can arrive home in-between trips. The actual amount of unique drivers that start the day with their first trip from their departure destination and arrive at home at the end of the day is 13,650. Furthermore, single trip distances of over 100 km are reduced to a value of 100 km, since larger single trip distances are considered unrealistic for the case of Aruba. This dataset is then scaled to represent the average Aruban daily driving distance of 41.7 km.

From this data, driving profiles are constructed that represent driving cycles. These profiles indicate how many kilometers are driven in each 1-hour time step. This is subsequently used to calculate how much energy is required to recharge the battery and to keep the SOC of the vehicle within its set boundaries. It is also used in the case of optimised charging to determine when a car is on the move and thus cannot charge, and when it is idle and thus has the option to charge. The dataset is limited to 500 EVs for computational purposes, but the characteristcs still represent those of the original dataset. The average daily driving distance is kept the same, an average of 41.7 km for all types of personal vehicles on Aruba [124]. An example of this is depicted in figure 5.9 which represent the total driven distance per time step for 500 EVs.

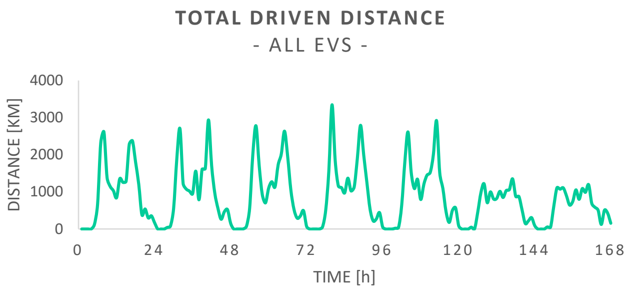


Figure 5.9 Total driven distance of 500 simulated EVs in the model, depicted for one week.

Battery behaviour

This section will be devoted to explain the physics that govern battery behaviour and how these are modelled. All of these characteristic are dependent on type (and material) of the battery used. For the EVs currently in the market, the most commonly used technology is a Li-ion based battery system. This is expected to remain the first choice in the future [158]. Therefore, in this thesis only this technology is considered. In general, battery behaviour can be explained by i.a. the following characteristics:

- Allowed (dis)charge rate depends on SOC
- Allowed (dis) charge rate depends on total capacity
- Allowed (dis) charge rate limited by electronics (e.g. inverter)
- Temperature and humidity affect the battery behaviour
- Battery experiences self-discharge
- Charge efficiency depends on battery and electronics
- Degradation due to cycling

The energy content within the battery can be denoted by a dimensionless number called the state-of-charge *SOC* and is defined as:

$$SOC = \frac{Q(t)}{Q_0} \tag{5-58}$$

Where $Q(t)$ is the amount of charge at time t, and Q_0 is the nominal capacity of the battery in kWh [49]. The difference in SOC due to charging or discharging is related to the charge power $P_{charge}(t)$, the nominal capacity Q_0 and the charge time period from t_1 to t_2 such that:

$$\Delta SOC = \frac{1}{Q_0}\int_{t_1}^{t_2} P_{charge}\,(t)\,dt \tag{5-59}$$

The energy that can be taken from a battery is limited to the situation where roughly 95 percent of the actual stored energy in the battery is released, and the voltage would drop rapidly if the discharge were to continue. [159]. These deep-discharges have a severe impact and the induced stresses reduce battery lifetime. In fact, battery lifetime has a non-linear relation to the depth-of-discharge (DoD) given in SOC value, i.e. halving the DoD more than doubles battery lifetime.

To prevent large reductions in calendar life, the depth-of-discharge of the battery system is limited. To what value this is done differs in practice, but is roughly in the range of 10% to 20% SOC [160,161].

The capacity Q_0 that can be taken from a battery depends on the current at which it is discharged. This is called the Peukert effect. To be able to compare different batteries, this current is normalised and given as the C-rate. A 1.0C discharge rate denotes a scenario in which the battery is fully discharged within one hour. A scenario with a C-rate of 0.2 on the other hand, takes 5 hours. For larger currents, the voltage decrease through discharge is larger and the maximum battery capacity will therefore be smaller: at 2C roughly 10% decrease in capacity. The standardised battery capacity given on a product is obtained from a 0.2C discharge. This effect for different C-rates is included in appendix 3. In this thesis, only the discharging of the battery when connected to charging infrastructure is affected, not while driving. The rate at which the battery is discharged is thus limited to the power capacity of the vehicle-to-grid charging infrastructure. It is assumed discharging for V2G purposes will never surpass a 1C discharge rate. In the case of a 25 kWh Nissan Leaf that would indicate a discharge power of 25 kW. Consequently, only the region between 0.1C and 1C is of interest. In this region, there is a negligible difference in capacity that can be released from the battery. This can be seen in both figures in appendix 3. The effect of discharge rate on maximum energy capacity is therefore ignored.

Reduced battery capacity due to cycling degradation is not taken into account, since the time frame in this thesis is limited to a one-year time frame. In a multi-year analysis, this would effect the battery capacity significantly, but within this time window the effect is marginal. Furthermore, self-discharge when not in use is assumed to be small and constant [163]. Therefore, the effects of these influences on the results are believed to be small and are not taken into account.

The discussed modelling assumptions are summarised below. These can be contrasted to the battery physics on the previous page.

Overview of assumptions:

- Constant battery voltage
- Capacity of the battery is not dependent on the discharge current (no Peukert effect)
- Capacity for continuous discharge equals capacity for intermittent discharge (no Recovery effect)
- Temperature and humidity do not affect the battery behaviour
- Self-discharge of the battery is not included in this model
- Degradation due to cycling is not included
- Depth-of-discharge is limited to a minimum 20% SOC

Charging process

This thesis does not go into details of the charging process, and therefore the following adaptations have been made to simplify the charging process. The charging method that is used is the so-called CC/CV charging process. This indicates that in the first stage, the charge current is constant (CC) and in the second stage the charge voltage is constant (CV). This is depicted in Figure 5.10. The current is exponentially decreased in the second stage. Through eq. 5-53 we conclude that the state-of-charge will sharply increase in the beginning, but its slope will gradually decrease to zero while it approaches 100%. This last part is called *tapering*.

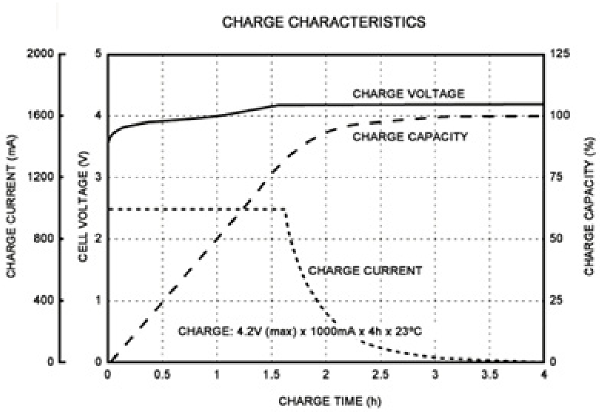


Figure 5.10 Schematic depiction of CC/CV charging process and its characteristics.

The origin of this charge profile is due to the resistance-induced heating effects inside the battery when it gets close to a full charge. To prevent overheating and thus thermal damage to the battery cells, the current is limited in the second stage. The transition point between the two stages will depend on the charge power, the chemistry, temperature and design of the battery. At a lower power and for example in winter, the transition point can occur at significantly higher SOC. Multiple adaptations of this charge profile exist and different charger manufacturers use slightly different curves specifically suited to their battery product. Moreover, the charger will dynamically adapt its charge current to the information supplied by the battery management system to prevent damage.

Since the effect of different charge strategies is the main aim of this thesis, the charging is limited to Level 1 and Level 2 charging. DC fast-charging (Level 3) is not considered since it does not provide flexibility for controlled charging or vehicle-to-grid. This type of charging is only used by vehicle users that are *en route* and need a fast refill. Since the user wishes to minimize waiting time, this happens at the maximum possible charge power. In the case of controlled or smart charging, the power to the vehicle will depend on the availability of renewable energy sources and/or the price of electricity. A difference in power from this original fast-charging situation therefore automatically means a longer waiting time. More notably, supplying power back into the grid through V2G will increase the waiting time even more. Thus, a user that aims to quickly recharge his vehicle, is believed not to participate in these schemes.

Therefore, in this thesis the choice has been made to focus on and compare three different charge levels, as summarised in table 5.3. These practical implementation of these levels is confirmed by grid operator ELMAR [163] and similar values were used in the study performed by Diaz et al. [60].

Table 5.3 Overview of power levels considered in this thesis.

Power level	Description
1.5 kW	low-power home charging, based on regular 120 V home outlet
7 kW	high-power home charging and low-power public or workplace charging, based on special, but commonly implemented, 240 V outlet
21 kW	high-power public or workplace charging, based on split 3-phase connection, achievable within low voltage grid

As distances are small on Aruba and the average daily driving distance based on a yearly average for personal vehicles is only 41.7 km, the required energy to recharge the battery is around 7.1 kWh, respectively, based on a 0.17 kWh/km efficiency. At a charge rate of 1.5 kW, this would mean charging times of less than 5 hours. Or 1 hour at a charge rate of 7 kW. Note that these are still very moderate rates compared to present-day 50 kW fast-charging and 100 kW fast-charging possible at Tesla's Supercharger stations that are now becoming widespread in Europe. These short times indicate that- for average use- recharging can easily be achieved during nighttime or when parked at the workplace. This means that from a system perspective there is very little need for Level 3 fast-charging on Aruba. This does not mean that there will not be any demand for fast-charging on the island.

Overview of assumptions:

- Only AC charging is considered
- Only level 1 and level 2 charge powers are considered, with a maximum of 21 kW.
- The charge voltage is assumed to remain constant throughout the entire charging process
- The power to the battery can vary between 0 and P_{max} in the case that only charging is considered and between $-P_{max}$ and P_{max} when a V2G scenario is considered
- The charging efficiency is assumed to be 92%, based on the electrochemical and power electronics efficiencies, both roughly 96%

Charging stations

In the model the assumption is made that each EV is able to make use of public daytime charging at each possible moment. This would assume a theoretical 50,000 public charging stations. Despite the fact that EV owners usually occupy a charging station longer than the net required charging time, such a large number is not necessary to accomodate large-scale EV charging. Charging stations can be shared and thus less will be needed. To give insight into this requirement, an overview of simultaneous charging in time is depicted in figure 5.11 and as a duration curve in figure 5.12. These figures depict the share of EVs charging simultaneously at each time step. Note that this is active charging time and not possible extra time connected to the charger. The average for this time period is 13%. In the figures a limit of 50% is introduced to show the practical implementation of 25,000 public stations.

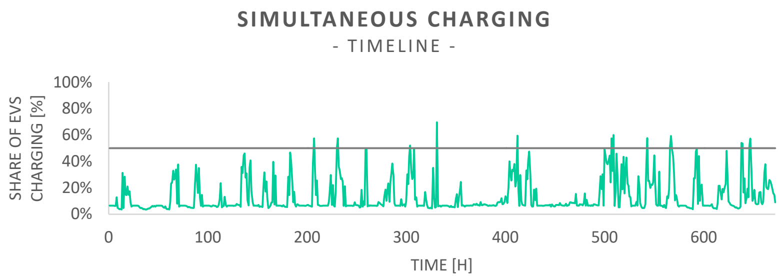


Figure 5.11 Simultaneous EV charging in model, depicted as timeline.

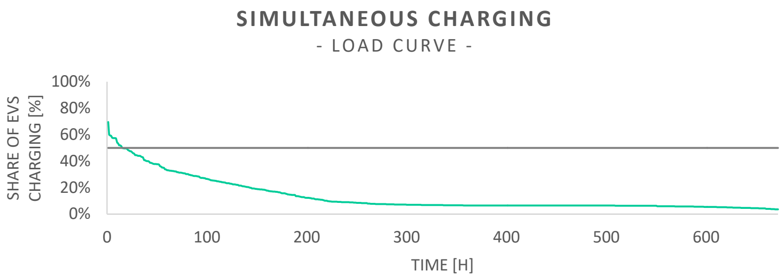


Figure 5.12 Simultaneous EV charging in model, depicted as load duration curve.

What is visible from these figures is that with half of the initially assumed charging stations in place, the share of EVs charging simultaneously very rarely exceeds the 50% limit. This gives a more realistic estimation of the needed public charging stations. Thus, this number of 25,000 charging stations is used in the economic analysis in this thesis, as a very conservative amount in the following depicted economic indicators. In reality, this number may be smaller by sharing through e.g. valet charging [164].

5.7 Cost calculation

Levelised cost of electricity

To compare different cases for the electric system cost, the levelised cost of electricity (LCOE) is a commonly used benchmark. The formula used here to calculate the simplified LCOE for a given technology over its lifetime is stated in eq. 5-60 with $LCOE_{tech}$ in EUR/MWh [165]. Where $I_{o,tech}$ are the investment costs, only present in year 0, $M_{t,tech}$ are the operational costs including maintenance, $F_{t,tech}$ are the fuel costs, $P_{t,tech}$ is the installed capacity, $E_{t,tech}$ is the energy produced, r is the discount rate, t is the year and n is the lifetime.

$$LCOE_{tech} = \frac{\dfrac{I_{0,tech} * P_{tech} + \sum_{t=1}^{n} M_{t,tech} * P_{tech} + F_{t,tech} * E_{t,tech}}{(1+r)^t}}{\dfrac{\sum_{t=1}^{n} E_{t,tech}}{(1+r)^t}} \tag{5-60}$$

The combined LCOE of all generation sources *sLCOE* can be calculated through a weighted summation of the LCOE values of the individual technologies, based on their share of total energy production.

$$sLCOE = S_{gas} * LCOE_{gas} + S_{wind} * LCOE_{wind} + S_{solar} * LCOE_{solar} \tag{5-61}$$

The resulting LCOE values for different technologies then become:

$$LCOE_{HFO} = 183 \tag{5-62}$$

$$LCOE_{gas} = 218 \tag{5-63}$$

$$LCOE_{wind} = 31 \tag{5-64}$$

$$LCOE_{solar} = 82 \tag{5-65}$$

The choices and assumptions leading to these values will be discussed in the following sections.

General parameters

For all technologies, the system lifetime is estimated at 20 years. The produced energy of the specific technology depends on the installed capacity of the simulated scenario. The discount rate is assumed to be a somewhat conservative 6%, based on [166].

Cost data

WEB Aruba [167] provides figures for fuel, maintenance & operation (M&O) costs and depreciation expenses for conventional HFO-based power production. Values for wind and solar are collected from [10]. These cost data used for the calculation are summarised in table 5.4 for the analyzed technology types.

Table 5.4 Overview of cost assumptions for different technologies.

Technology	**Investment cost** [EUR/kW]	**Fuel cost** [EUR/MWh]	**M&O + depreciation** [EUR/kW]
HFO	0	145	105 + 90
Gas	0	218	105 + 90
Wind	1415	0	36
Solar	1550	0	11

HFO generation

Since there are no specific values available for each type of generation (steam turbine, recip and peak engines), different LCOE estimates are attributed to each type of generation in the model. A higher value than combined average for steam and peak power, and a lower value for recip power. These are values estimated based on their efficiencies and are depicted in table 5.5. As is clear, the combination gives the same combined LCOE, This difference is important for the analysis of the high renewable penetration scenarios since then the distribution of power from each source will change, i.e. peak and recip will be replaced by renewable generation, and steam power will only be reduced marginally as this is needed to remain grid stability.

Furthermore, for conventional power generation the depreciation costs are taken into account as annual costs with the M&O expenses. These are assumed to be 75% of total depreciation expenses as stated in [167]. Hence the investment costs are assumed to be zero. This is done to represent the situation on Aruba with existing power generation units that need not be replaced.

Table 5.5 Overview of generation shares, LCOE values and their ratio compared to the average for the current (2015) situation.

Technology	**Generation share** [%]	**LCOE** [EUR/MWh]	**Ratio** [%]
Steam, HFO	33.1%	195	106%
Recip, HFO	27.2%	170	93%
Peak, HFO	25.2%	185	101%
Total	85.5%	183	100%

Gas generation

In the scenarios analyzed in this thesis, the fuel used for conventional power generation is liquefied natural gas (LNG). Its cost figures are based on those of HFO production. M&O costs, including depreciation is assumed to be the same, as the same machinery is used, but fuel cost is assumed to be 150% of HFO-based production. The adapted LCOE values for gas-based production are depicted in table 5.6. These gas-based LCOE values correspond to LCOE values found in [169] where LNG is evaluated for Caribbean island San Andres as alternative to diesel.

Table 5.6 Overview of LCOE values and their ratio compared to the average for a future gas-fueled production situation.

Technology	**LCOE** [EUR/MWh]	**Ratio** [%]
Steam, gas	230	106%
Recip, gas	202	93%
Peak, gas	220	101%
Total	218	100%

In the overall economic analysis, the different conventional power generation will presented as a single group.

Wind and Solar

The data for the investment and M&O cost for both renewable sources are directly adopted from [10].

Cost of charging infrastructure

These costs for the charging infrastructure can be included into the system LCOE by implementing the same approach as for power generation. Here a similar method is followed as performed in [101], where the annual and capital cost are compared to the savings on fuel expenditure. However, in this thesis, these costs are normalised by the total system energy. This is presented in eq. 5-66, where $LC_{,ch.infra}$ is the levelised cost of charging infrastructure, $I_{o,ch.infra}$ are the charging infrastructure investment costs, only present in year 0, $M_{t,tech}$ are the operational costs including maintenance, but also data & payment services, $E_{t,system}$ is the total system energy produced, *r* is the discount rate, *t* is the year and *n* is the lifetime.

$$LC_{ch.infra} = \frac{\dfrac{I_{0,ch.infra} + \sum_{t=1}^{n} M_{t,ch.infra}}{(1+r)^t}}{\dfrac{\sum_{t=1}^{n} E_{t,system}}{(1+r)^t}} \tag{5-66}$$

This can subsequently be included into a new cost value *sLC,* to give a combined levelised cost for the power generation system and charging infrastructure, presented in eq. 5-67:

$$sLC = sLCOE + LC_{ch.infra} \tag{5-67}$$

The choices and assumptions used in this calculation will be discussed in the following sections.

Cost data

RMI [170] have performed an extensive analysis into the current cost of charging infrastructure in the US. The authors indicate that AC level 2 (~7 kW) charging stations cost on average 9200 USD per public charging pole, for a curbside installation. This means that the charger is installed on the side of the street, conversely to for example the installation in an indoor public parking garage. These are combined cost of hardware, material, labour, mobilisation and permitting costs. A reduction for a dual installation results in a total cost per connection of 5800 USD. This is a single pole with two vehicle charge connections. Thus resulting in lower cost per connection, because of shared labour, mobilisation, permitting cost. Of these, the charger hardware and labour costs are the largest, amounting to 40% and 55% of the total costs per pole, respectively. The periodical costs for maintenance and operation, but also data and communication service are estimated at 300 USD and 250 USD, respectively. A standard 1.5 kW outlet charger is included in the purchase of the EV and therefore the cost is effectively zero. These figures for are summarised in table 5.7 and 5.8.

Table 5.7 Overview of charging infrastructure investment cost provided by RMI [170]

Power level	**Charger type**	**Cost per connection**			
		Min	Max	Average	Dual installation
1.5 kW	Home	$ 0	$ 0	$ 0	-
7 kW	Home	$1000	$1500	$1200	-
7 kW	Public curbside	$8000	$10000	$9200	$5800

Table 5.8 Overview of periodic charging infrastructure cost provided by RMI [170]

Periodic costs	**Cost per connection** [$/year]
Maintenance & operation	$300
Data & payment service	$250

Similar to the case of the US, The Netherlands Knowledge Platform for Public Charging Infrastructure (NKL) [171] has evaluated the costs of charging infrastructure for the case of The Netherlands and for multiple years: 2013, 2016 and 2020. These figures for are summarised in table 5.9 and 5.10. These are based on a dual installation of an AC 9 kW connection per vehicle with smart charging capability (= flexible charge rate based on electricity system input). Including charge efficiency this becomes roughly 8 kW and thus is representative for the 7 kW charge infrastructure analyzed in this thesis. In their analysis, the total installation costs are split up similarly in a 40% share for the hardware and 45% for labour costs, for 2016.

The cost reductions from 2013 to 2016 have been 30%, of which the main causes are standardization of placement process, economies of scale and lower maintenance costs through increased product quality. This trend of cost reduction is predicted to continue and the cost of public charging stations will decrease further. Interestingly, RMI does not take into account any periodic costs for the grid connection, whereas the NKL indicate that this amount to € 210 per year.

Table 5.9 Overview of charging infrastructure investment cost provided by NKL [171]

Power level	**Charger type**	**Cost per connection** Min	 Max
7 kW	Public curbside – dual installation [2013]	€4655	-
7 kW	Public curbside – dual installation [2016]	€3450	-
7 kW	Public curbside – dual installation [2020]	€2000	€3000

Table 5.10 Overview of periodic charging infrastructure cost provided by NKL [171]

Periodic costs	**Cost per connection** [€/year]
Maintenance & operation	€200
Data & payment service	€65
Grid connection	€210

General parameters

Similarly to generation technologies, the system lifetime is estimated at 20 years and the discount rate is assumed to be 6%.

Based on these sources, the investment and periodic costs of charging infrastructure are estimated for the case of Aruba. These figures are summarised in table 5.11 and 5.12. An overview of the choices and assumptions leading to these figures is given below:

Table 5.11 Overview of charging infrastructure investment cost assumptions

Power level	**Charger type**	**Cost per connection**		
		Uncontrolled	Controlled	V2G
1.5 kW	Home	€0	€250	€500
7 kW	Home	€1200	€1250	€1750
7 kW	Public curbside	€2500	€2500	€3500
21 kW	Public curbside	€4500	€4500	€6300

Table 5.12 Overview of periodic charging infrastructure cost assumptions

Periodic costs	**Cost per connection** [€/year]
Maintenance & operation*	€200
Data & payment service**	€50

*   are only included for public charging stations
** are included for controlled and flexible charging connections, both home and public

Overview of assumptions:

- Charge infrastructure costs are mainly based on the dual installation cost figures provided by [171].
- Large-scale distribution grid reinforcement costs to accomodate EV charging are not included.
- Cost estimates are based on level 1 and level 2 AC charging. Therefore, there are no costs included for e.g. DC converters.
- For the 1.5 kW home charge connection, the cost for an intelligent charge unit are estimated at €250, which is needed to make regular power outlet charging controlled. The addition of control to the 7 kW home connection and both requires more advanced hardware and control. The extra costs are estimated at €50 on top of the €1200 for 7 kW home charging.
- The extra costs of adding control to the 7 kW and 21 kW public connection are assumed to be zero, as in the future this capability is expected to be standard for this type of infrastructure.
- For high power public charging station infrastructure of 21 kW, the extra costs are estimated to be in the order of magnitude of €2000 (includes service drop and upgrade of 25 kVA pole mount transformer to 75 kVA) based on [172] where a 19 kW load addition is considered for a case in the US.
- For the addition of V2G capabilities, there have not been found clear cost estimates, since only test cases and pilots exist. However, the rule of thumb [173] states that hardware costs will double due to more advanced charge pole hardware and control. Data communication and payment service is assumed to not be substantially more than a charging connection with controlled flexible charging. Therefore, the initial 40% hardware costs as included by NKL are doubled to estimate the cost oper charge connection for V2G capability. The bi-directional inverter that needs to be included in the vehicle is assumed to be present in the V2G scenarios.
- Maintenance and operation costs are assumed to be €200 per year for all public charge connections and data and payment services are assumed to be €50 per year for all controlled charging connections. For the case of Aruba, periodic grid connection costs are not taken into account.

5.8 Emissions calculation

Effects on emissions can be calculated using estimates for emissions per energy unit produced. These emission values are given in ton CO_2-eq. per GWh electricity produced for electricity generation units. The CO_2 equivalent includes the effect of other gases such as nitrogen oxides, sulphur-oxides, methane, etc. Furthermore, these values are equivalent emissions based on the full lifecycle of electricity generation, so including cultivation and fabrication, construction, operation and decommissioning. Naturally the actual values for emissions will depend on a wide variety of factors such as used materials, efficiency, location and weather conditions, longevity and much more. However, in this thesis estimates are used for the emission values. The produced results will therefore rather indicate an estimate for emissions reductions than a precisely predicted value. Gagnon et al. [174] provide an overview of average life cycle emission values for fossil-fuel based generation sources. Mean values for life cycle wind and solar PV production emissions are given by Nugent & Sovacool [175]. These mean values are based on a survey of a total of 153 studies. These emission rates are summarised in table 5.13.

Table 5.13 Overview of life cycle emissions for different electricity generation technologies [174,175].

Source	Type	Life cycle emissions [g CO_2 eq./kWh_e]
Natural gas	Various combined cycle turbines	443
Diesel	Various generator and turbine types	778
Heavy oil	Various generator and turbine types	778
Wind	Mean	34.1
	- Onshore	38.9
	- Offshore	18.9
Solar PV	Mean	49.9
	- Crystalline silicon (c-Si)	55.3
	- Thin-film	20.9

In this thesis, the values used for wind and solar power are 19 and 40 g CO_2 eq/kWh, respectively, based on offshore wind power and a mix between crystalline silicone and thin-film solar PV. Offshore wind has been chosen, since the island situation of Aruba effectively represents an offshore situation with a substantial wind resource.

Real-life emissions for motorised emitters are reported per km driven for internal combustion engine (ICE) vehicles. These values can refer to solely CO_2 emissons in g CO_2/km or total equivalent greenhouse gas emissions in g CO_2-eq/km. Table 5.14 summarises emission values for real-life CO_2 emission averages in the US [176] and CO_2-eq emission estimates for Aruba [112] per fuel and vehicle type. The CO_2 and total equivalent emissions for full-electric vehicles are zero. It should be noted that these vehicle emission values are direct emissions, not lifecycle emissions. Moreover, these are real-life emissions, and so considerably higher than reported average laboratory emissions. For example, in 2015, the EU limit for laboratory emissions of new vehicles was 130 g CO_2/km, and in 2021 this will be 95 g CO_2/km [2].

Table 5.14 Overview of real-life CO_2 emission averages for the US [176] and total eq. GHG emissions for Aruba [112], per vehicle and fuel type.

Source	Type	CO_2 emissions [g CO_2/km]	GHG emissions [g CO_2 eq./km]
Gasoline	Personal vehicle	220 [176]	386 [112]
Diesel	Personal vehicle	154 [176]	(not provided)
Gasoline	Light truck	319 [176]	528 [112]
Diesel	Light truck	225 [176]	430 [112]
Full electric	Personal vehicle	0	0

For the case of Aruba, due to lack of restrictions on or standards for vehicle emissions, a relatively high fraction of light trucks (SUVs), continuous use of air-conditioning and poor quality gasoline fuel, as was stated in section 4.3, the combined average value used for gasoline and diesel powered vehicles is assumed to be 300 g CO_2-eq/km.

6. OPTIMISATION

6. OPTIMISATION

In this chapter the used optimisation approach for controlled EV charging is explained. It will outline the choices made for the approach as well as for the implementation.

Engineering optimisation problems can be very complex and difficult to solve by hand. Mathematical programming can be used to solve this problem and find an optimal solution.

In principle each optimisation problem can be described by specifying:

1)	Decision variables	(degrees of freedom)
2)	Objective function	(performance criterion)
3)	Equality and/or inequality constraints	(constraints)

In which the objective function depends on the decision variables and a number of constants.
The whole problem is subject to a set of constraints of that are again a function of the decision variables and a number of constants. The largest or smallest value of the objective function is called the optimal value, and a collection of values of decision values that gives the optimal value is called an optimal solution. [177]

6.1 Dynamic optimisation

The optimisation problems as described above have static character, i.e. the optimisation variables are constant and thus independent of time. In the case of electric vehicle charging, the goal is to find an *optimal policy* or *optimal time-dependent path* that constitutes the set moments and rates at which charging is optimal – defined by the objective function – within the given set of constraints and based on a system equation, over a certain time interval. This is called a *dynamic optimisation problem.* A dynamic problem can be visualised through the schematic diagram depicted in figure 6.1.

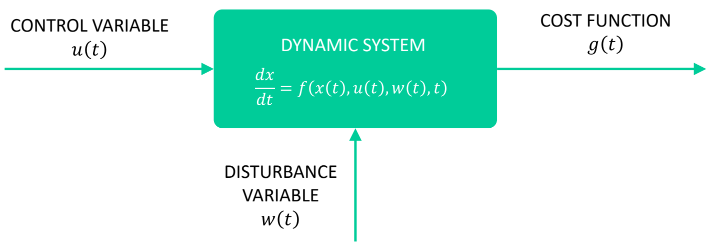


Figure 6.1 Schematic diagram of a dynamic system.

In the case of a dynamic problem, such a system equation or transition function is added to the three basic elements of an optimisation problem. It describes the model behaviour, i.e. how a next state depends on a previous state, the action taken during that time step and a possible external uncontrollable influence. A state describes *"all the information required to fully assess the consequences that the current decision has upon future actions."* [178]. Another change to the original static optimisation formulation is that the decision variable is now called the control variable. Since this will be a set of variables for the given time interval it will be a in vector format, and is thus called *control vector* or *steering vector.*

In summary, the definition of the dynamic optimisation problem contains:

1)	Control vector *u(t)*	(degrees of freedom)
2)	Objective function *J*	(performance criterion)
3)	Equality and/or inequality constraints	(constraints)
4)	System equation *f(u, x, w)*	
5)	State variables *x(t)*	
6)	Initial and final time determination $[t_0, t_f]$	

Several mathematical techniques have been developed to solve dynamic optimisation problems. The fundamental approaches are [179]:

- Variational Calculus
- Pontryagin's maximum principle
- Dynamic programming

Of these methods, both Variational Calculus and Pontryagin's maximum principle lead to an analytical solution that is difficult, read impossible, to solve. Dynamic Programming (DP) formulates an algorithm that deals with the problem in a sequence of smaller, discrete steps that are easier to solve [178]. That way it makes it possible to solve difficult (non-linear) problems.

Dynamic programming

This form of programming has been introduced by Bellman in 1957 [180]. It makes use of the Principle of Optimality as defined as: *"An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision." [180]*

Using this principle of optimality, an algorithm can be formulated, that describes a recursive relationship for computing the optimal-value function at each moment, i.e. the decision in a particular state is determined simply by choosing the minimal total cost. It starts from the end-state and makes its way back to arrive at the initial state. After each step it stores the solution in the so-called cost-to-go function. This summarizes all the information needed for the next steps and makes other information regarding previous stages obsolete. In more general terms, this approach discretizes the time interval into N number of stages. It then *"builds to a solution of the overall N-stage problem by first solving a one-stage problem and sequentially including one stage at a time and solving one-stage problems until the overall optimum has been found. This procedure can be based on a backward induction process, where the first stage to be analysed is the final stage of the problem and problems are solved moving back one stage at a time until all stages are included." [178]*

The counterpart of backward induction is forward induction. The method is the same, but the direction is the opposite: the first stage to be analysed is the first stage of the problem and problems are solved moving forward one stage at a time until all stages are included. The number of states and stages influences the time needed to solve the problem. In many physical models the state space, i.e. the set of possible states, is continuous and would thus lead to an infinite number of states at each stage. Therefore, the state space is made smaller by using a discrete approximation of the set of possible states. The same technique can be applied to the control variable. The size of the state space and the set of possible control actions directly affect the computational effort needed to solve the problem.

An example of a minimization problem formulation is given here [181]. The variable *k* denotes the different stages in the optimisation problem.

Find the optimal control sequence π^* for the specified initial state x_0 :

$$\pi^*(x_0) = \{u_0^*, u_1^*, \ldots, u_{N-1}^*\} \tag{6-1}$$

$$x_0 = \mathrm{x(t = 0)} \tag{6-2}$$

By minimizing the total value function of the cost for the last step $g_N(x_N)$ and subsequently for the recurring steps, according to:

$$J(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, w_k) \tag{6-3}$$

Subject to the transition function f_k and the limitations to the state-space X_k and control vector U_k:

$$x_{k+1} = f_k(x_k, u_k, w_k) \tag{6-4}$$

$$x_k \in X_k \tag{6-5}$$

$$u_k \in U_k \tag{6-6}$$

This implies that the cost of the last step $J_0(x_0)$ denotes the optimal total cost $J^*(x_0)$.
The discretization of the state-space region [181] can be depicted as done in figure 6.2.

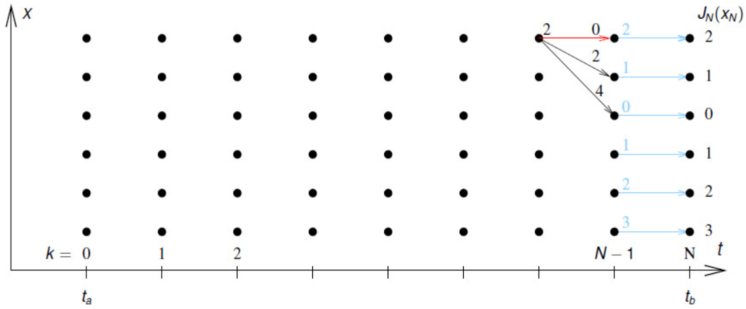


Figure 6.2 Depiction of discretization of state-space region [181].

The state-space grid with all paths that are evaluated is depicted in figure 6.3. In this example, the maximum possible step (change in state) is two.

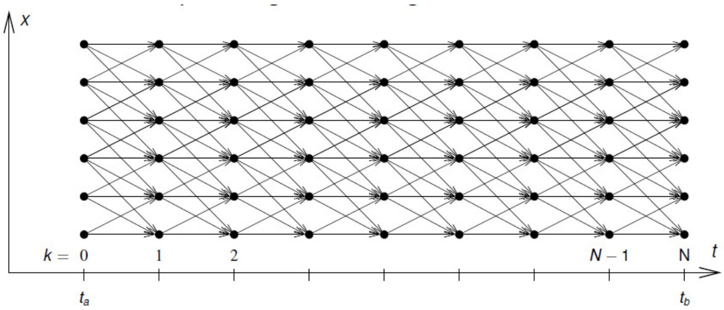


Figure 6.3 Depiction of discretization of state-space region with all possible paths indicated [181].

It shows the functioning of the algorithm, which operates as follows:

1. Set $k = N$, and assign final cost $J_N(x_N) = g_N(x_N)$
2. Set $k = k - 1$
3. For all point in the state-space grid, find the optimal cost-to-go, according to:

$$J_k(x_k) = \min_{u_k \in U_k(u_k)} g_k(x_k, u_k) + J_{k+1}\big(f_k(x_k, u_k, w_k)\big) \tag{6-7}$$

4. If $k = 0$, then return solution
5. Go to step 2

The algorithm calculates the paths through the state-space grid, starting from each possible end-state. The user then specifies the initial state, which leads to the choice for one of these paths, which is the optimal policy of decision to be taken starting from the given initial state to the unconstrained and now determined end-state.

Model Predictive Control

Another new way of dealing with these problems is through an equal merger of Integer Programming (IP) and DP as presented by Martin et al. [182]. Prior to this study, unequal combinations have been presented, where the IP (or linear program) was a master and the DP was a subproblem [183].

This approach represents the dynamic program as a linear programming problem with a polynomial number of variables. The linear programming formulation obtained from the dynamic program provides a polyhedral description of the model considered [184]. The optimal solution can thus be found via a multitude of conventional algorithmic approaches that are commonly used by optimisation software programs (solvers), such as GAMS and Ilog CPLEX.

In dynamic problems, Model Predictive Control (MPC) can subsequently be used to provide an optimal solution for a given time interval. This makes use of a receding horizon strategy for the optimisation problem, where a new 'optimal' policy is calculated at each discrete time step. This strategy is graphically depicted in figure 6.4 [168].

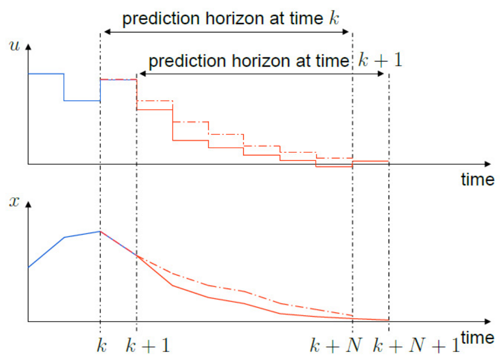


Figure 6.4 Model Predictive Control with receding horizon strategy [168].

This method of rewriting a dynamic problem in the form of a linear problem *"provides an advantage of easily writing and solving tractable DP models using commercial software."* [184]. However, it does mean that the actual methodology of the algorithm is hidden from the user.

6.2 Choice of optimisation strategy

In this thesis the choice has been made to implement dynamic programming as the method for optimisation of controlled EV charging. The reason is it gives more flexibility and understanding of the process that is used to arrive at a certain solution, i.e. charge profile.

In terms of the direction of the algorithm, backward induction will provide an optimal value for a constrained initial state-of-charge at t_0 to an unspecified final value for state-of-charge at $t_f = T$, whereas forward induction will provide an optimal value for a given fixed final state-of-charge for an unconstrained initial state-of-charge. Obviously, since it is physically impossible to change the initial state-of-charge, backward induction is chosen.

6.3 Application to EV charging

In this section will be outlined how DP is implemented for the use of controlled EV charging. This is based on the method implemented in [102]. A fundamental assumption is that the model is deterministic, i.e. there is no uncertainty about prediction of load and supply. Thus all information is available based on the calculated forecasts for each technology. The same therefore goes for the EV charging optimisation, which thus is deterministic.

Model simulations are run for with a time step of one hour. Therefore the discrete time steps used in the optimisation are also one hour time steps for $t = 1, 2, \dots, T$. The optimisation is run for a fleet of N vehicles, in which N is the total number of vehicles. Note the difference to the previous equations where $k = 1, 2, \dots, N$ was used as discrete time steps.

The used variables in this optimisation problem represent the following physical entities:

$$x_{n,t} = battery\ \text{SOC} \tag{6-8}$$

$$u_{n,t} = charge\ /\ discharge\ (V2G)\ power \tag{6-9}$$

$$w_{n,t} = discharge\ power\ due\ to\ driving \tag{6-10}$$

$$g_{n,t} = cost\ function \tag{6-11}$$

These variables are specific for each vehicle n and for each time step t. For EV charging, the following conditions and constraints apply. The next battery state-of-charge $x_{n,t+1}$ depends on the charge action $u_{n,t}$ and the discharge power due to driving $w_{n,t}$ according to eq. 6-12.

$$x_{n,t+1} = f_{n,t}(x_{n,t}, u_{n,t}, w_{n,t}) = x_{n,t} + u_{n,t} - w_{n,t} \tag{6-12}$$

The battery state-of-charge $x_{n,t}$ for each step is constrained to the set of possible states $X_{n,t}$ according to:

$$x_{n,t} \in X_{n,t} \tag{6-13}$$

$$X_{n,t} = [SOC_{min}, SOC_{min} + dx, \dots, SOC_{max} - dx, SOC_{max}] \tag{6-14}$$

And the charge action $u_{n,t}$ for each step is limited to the set of possible actions $U_{n,t}$, according to:

$$u_{n,t} \in U_{n,t} \tag{6-15}$$

$$U_{n,t} = \left\{ \begin{matrix} [0, \dots, P_{max} - du, P_{max}] \\ [P_{min}, P_{min} + du, \dots, P_{max} - du, P_{max}] \\ [P_{min}, P_{min} + du, \dots, 0] \end{matrix} \right\} \quad \begin{matrix} if\ x_{n,t} = SOC_{min} \\ if\ SOC_{min} < x_{n,t} < SOC_{max} \\ if\ x_{n,t} = SOC_{max} \end{matrix} \tag{6-16}$$

Where P_{min} and P_{max} depend on the chosen simulation scenario.

Similar to the example in section 6.1., the goal is to find the optimal charge control sequence π_n^* for the specified initial state $x_{n,0}$,

$$\pi_n^*(x_{n,0}) = \{u^*_{n,0}, u^*_{n,1}, \dots, u^*_{n,T-1}\} \tag{6-17}$$

$$x_{n,0} = x_n(\mathrm{t} = 0) \tag{6-18}$$

This is done based on the cost function $g_t(u_t)$ that relates the cost of charging to the residual demand through the dynamic price signal $\lambda(t)$ and the battery degradation cost C_{degr}. As stated in section 5.5, this price signal is recalculated based on the increased residual demand caused by EV demand. The degradation cost are taken as constant and with a value of 0.04 €/kWh [185].

$$g_{n,t}(u_{n,t}) = \left\{ \begin{matrix} \lambda(t) u_{n,t} \\ (\lambda(t) - C_{degr}) u_{n,t} \end{matrix} \right\} \quad \begin{matrix} if\ u_{n,t} \geq 0 \\ if\ u_{n,t} < 0 \end{matrix} \tag{6-19}$$

As an empty battery is not a permitted end-state, a linear function is implemented that assigns a cost to the final state of the battery according to:

$$g_T = C\left(1 - x_{n,t}\right) \tag{6-20}$$

Where any C large enough produces the desired result. The total electric vehicle demand $P_{EVs,t}$ is then calculated by adding up the charge profiles of the individual EVs:

$$P_{EVs,t} = \sum_{n=1}^{N} \pi_n{}^* \tag{6-21}$$

In the calculations mentioned here, the values and constants used are:

$$SOC_{min} = 0.2 \tag{6-22}$$

$$SOC_{max} = 1 \tag{6-23}$$

$$dx = 0.02 \tag{6-24}$$

$$P_{max\ ,home} = 1.5\ kW \quad for\ low\ power\ scenario \tag{6-25}$$

$$P_{max\ ,home} = 7\ kW \quad for\ high\ power\ scenario \tag{6-26}$$

$$P_{max\ ,public} = 7\ kW \quad for\ low\ power\ scenario \tag{6-27}$$

$$P_{max\ ,public} = 21\ kW \quad for\ high\ power\ scenario \tag{6-28}$$

$$P_{min\ ,G4V} = 0 \qquad for\ G4V\ scenarios \tag{6-29}$$

$$P_{min\ ,V2G} = -P_{max} \quad for\ V2G\ scenarios \tag{6-30}$$

$$du = 1\ kW \tag{6-31}$$

$$C_{degr} = 0.04\ €/kWh \tag{6-32}$$

7. RESULTS & DISCUSSION

7. RESULTS & DISCUSSION

7.1 Scenarios and cases

The technical performance and economic potential of controlled EV charging was analyzed for four different scenarios. These scenarios vary in the implementation of one-directional charging (G4V) or bi-directional charging (V2G) and the dominant renewable energy source used (wind or solar), as stated here:

- *G4V dominant wind*
- *G4V dominant solar*
- *V2G dominant wind*
- *V2G dominant solar*

The argument for these two separate dominant renewable resources is based on the following reasoning:

> Although (onshore) wind energy may represent Aruba's most cost-effective solution towards large shares of renewable energy, it may prove to be socially and culturally unacceptable to install these levels of installed capacity. Therefore, the island may need to make use of its other main asset: solar power. This alternative transition strategy is represented in the dominant solar power scenario.

The scenarios simulated are characterised by the following installed capacities of renewable energy sources summarised in table 7.1. In both cases these installed capacities lead to a *yearly average* renewable energy utilisation of 70% without including electric vehicles.

Table 7.1 Overview of installed capacities in the two 70% renewable energy penetration scenarios.

Installed capacities	**Scenario**	
Resource	*Dominant wind*	*Dominant solar*
Wind	160 MW	120 MW
Solar	60 MW	200 MW

The number of electric vehicles is taken as 50,000 vehicles to give the largest potential for controlled EV charging.

Furthermore, to identify what the effect is of adding controlled charging, public charging stations, and moving to a high power charging infrastructure, six cases were developed with varying charging infrastructure and control. These six cases were analyzed for each of the four scenarios stated above, and are given in table 7.2.

Table 7.2 Overview of charging infrastructure and control cases.

Case	**Control**	**Infrastructure**	**Power level**
0 – No EVs	-	-	-
1	Uncontrolled	Only home	-
2	Uncontrolled	Public & home	-
3	Controlled	Only home	LOW
4	Controlled	Public & home	LOW
5	Controlled	Only home	HIGH
6	Controlled	Public & home	HIGH

Availability of charging infrastructure and charge control

1) Control

Charging is modelled to be either controlled or uncontrolled. The latter entails that when an EV is parked the user immediately plugs in the vehicle at the arrival time and the charger will charge the battery at the maximum possible power limit. The former – controlled charging – is implemented to let charging happen at times when this is beneficial for the system through the price signal discussed in section 5.5. Furthermore, flexible charging is implemented, which entails that the charge power delivered to the vehicle can vary over different hours and both time and magnitude are optimised.

- controlled
- uncontrolled

2) Charging infrastructure

There is a division made between a situation where only at home charging is possible and a situation where both public or workplace and home charging both are possible:

- only home
- public&home

This difference reflects the availability of public and workplace EV charging infrastructure. The amount of available public or workplace charging station is assumed to be 25,000, see page 70.

3) Power level

In addition, a differentiation between two power levels is made:

- LOW 1.5 kW at home and 7 kW at public or workplace charging stations
- HIGH 7 kW at home and 21 kW at public or workplace charging stations

It is thus assumed that public or workplace charging will have a higher power capacity in both situations. Home charging happens only after the last home arrival. During the day the vehicle is asssumed to make use of daytime public or workplace charging facilities. For frequent and long-distance driving vehicles which cannot cover their energy needs with 1.5 kW charging at home, it is assumed that 7 kW charging at home is possible. This reflects an owner's investment in special charging equipment. This was needed for less than 10% of total amount of drivers.

4) G4V vs. V2G

The first case - G4V- entails only one-directional charging, whereas the second case - V2G- indicates bi-directional power exchange: charging and discharging. This means the EVs can perform the first of the V2G functions: peak shaving. This case of peak shaving is at first glance similar to the scenario where EV demand is a response to the residual demand to reduce peaks and valleys in the residual demand profile. However in this case a further reduction of the peaks in residual demand excluding EVs can be achieved by supplying power into the grid.

All of these case options are summarised in table 7.3.

Table 7.3 Overview of charging infrastructure and control case choices.

Scenario element	**-- Overview of choices --**	
Control	uncontrolled	controlled
Charging infrastructure	only home	public & home
Power level	LOW home 1.5 kW public 7 kW	HIGH home 7 kW public 21 kW
One- or bi-directional	G4V	V2G

7.2 Technical performance

The effect of these 4 scenarios and 6 cases on the key indicators (residual demand, curtailed energy, share of EV demand from curtailed energy and power generation emissions) was analyzed. The results are presented in the following sections. Firstly the results will be discussed for a G4V dominant wind scenario and for a G4V dominant solar scenario. Secondly, the same is done for a V2G setting.

General results

The results showed that a transition to 50,000 full-electric personal vehicles allowed an emissions reduction of 230 ktonCO_2-eq per year in direct emissions. This value is constant over the presented scenarios and cases.

Power generation emissions for the base case without EVs were reduced to 155 ktonCO_2-eq per year for the dominant wind scenario and to 165 ktonCO_2-eq per year for the dominant solar scenario. The current (2015) power generation emissions amount to roughly 550 ktonCO_2-eq per year.

Dispatch profile

In figure 7.1, the dispatch profile for a three day period without EVs is depicted for both the dominant wind power scenario and the dominant solar scenario. Note that in the dominant wind power scenario, wind provides the majority of power, supplemented by solar power during the day and by conventional power in the early morning.

In the dominant solar power scenario, its dominant source provides nearly all power during daytime (including some excess power at midday), supplemented by a substantial share of wind power and again a contribution of conventional power. In this scenario it is clear that there is more curtailed power compared to the dominant wind scenario.

By definition of the renewable penetration percentage of 70%, the contribution of conventional sources to the mix is 30% in both cases.

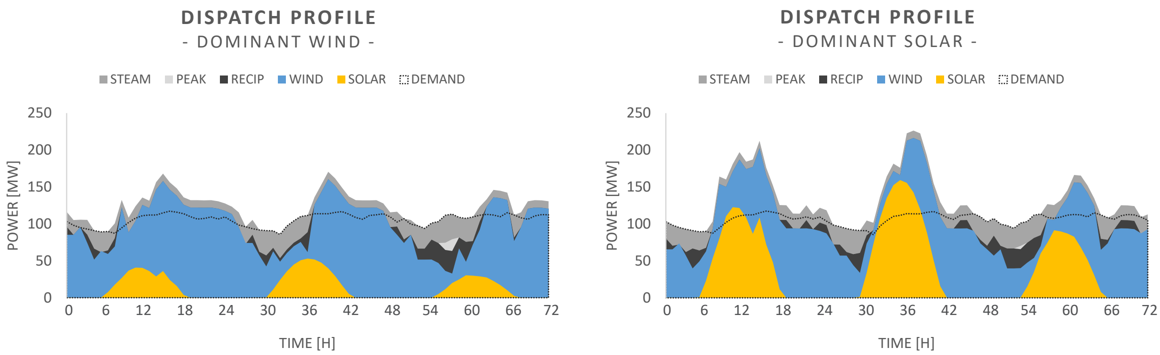


Figure 7.1 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b)

The effect of EV charging on the residual demand and the price profile for the four scenarios is presented on the following pages. This is done for the dominant wind and the dominant solar scenario in two separate graphs: (a) and (b) respectively. Firstly for an only home charging, secondly for public&home charging and thirdly for public&home charging with V2G.

Only home

Residual demand profile

The effect of controlled charging on the residual demand profile for only home charging is presented in figure 7.2.

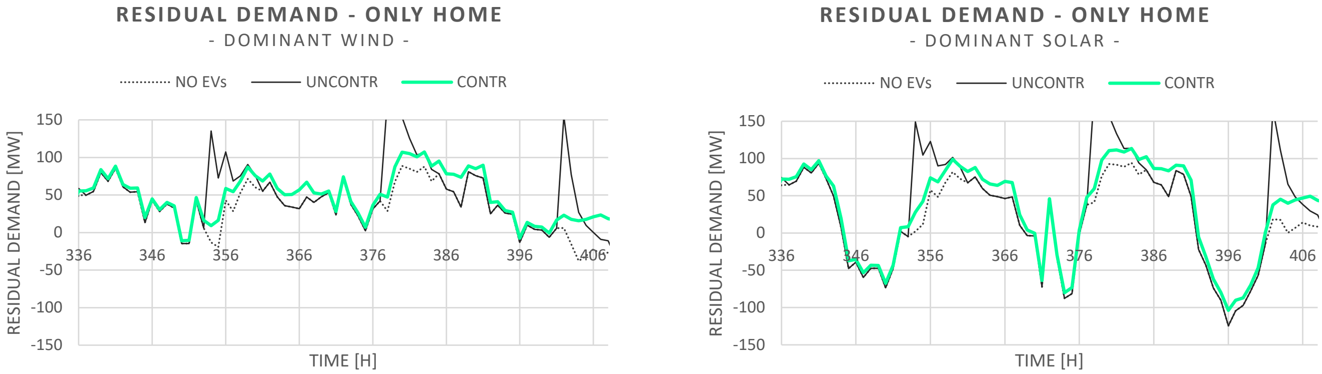


Figure 7.2 Residual demand profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) for only home charging, controlled and uncontrolled, and the base case with no EVs.

Public&home

Residual demand profile

The effect of controlled charging on the residual demand profile for public&home charging is presented in figure 7.3.

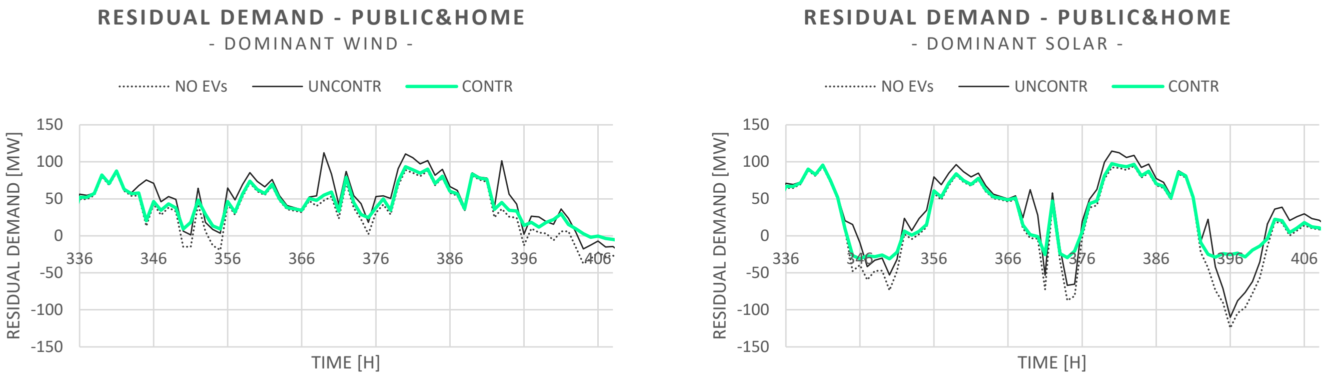


Figure 7.3 Residual demand profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) for public&home charging, controlled and uncontrolled, and the base case with no EVs.

Public&home with V2G

Residual demand and price profile

The effect of controlled charging on the residual demand profile for public&home charging with vehicle-to-grid (V2G) capabilities is presented in in figure 7.4. The effect on the dynamic electricity price profile is shown in figure 7.5. This shows three items: 1) the price with no EVs, 2) the price with EVs, which takes into account the inflation of the price due to EV demand, and 3) the battery degradation cost C_{degr}, which acts as a benchmark price.

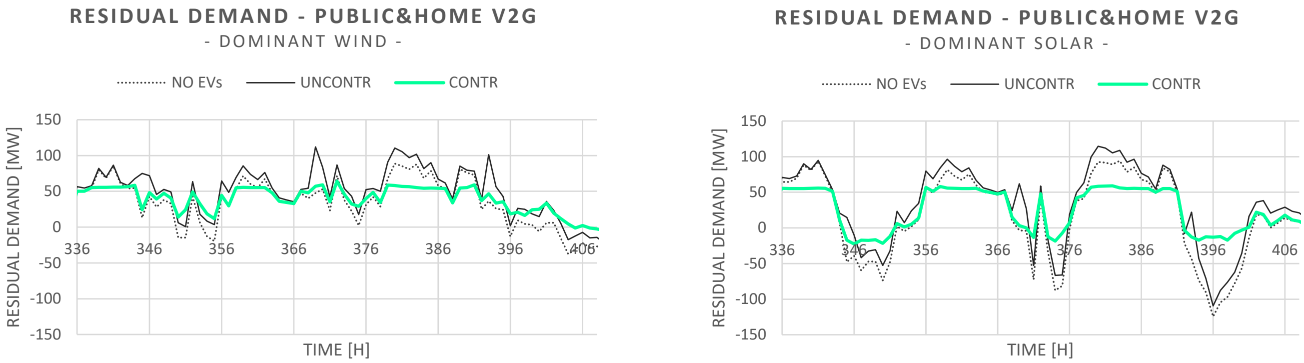


Figure 7.4 Residual demand profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) for public&home charging with V2G, controlled and uncontrolled, and the base case with no EVs.

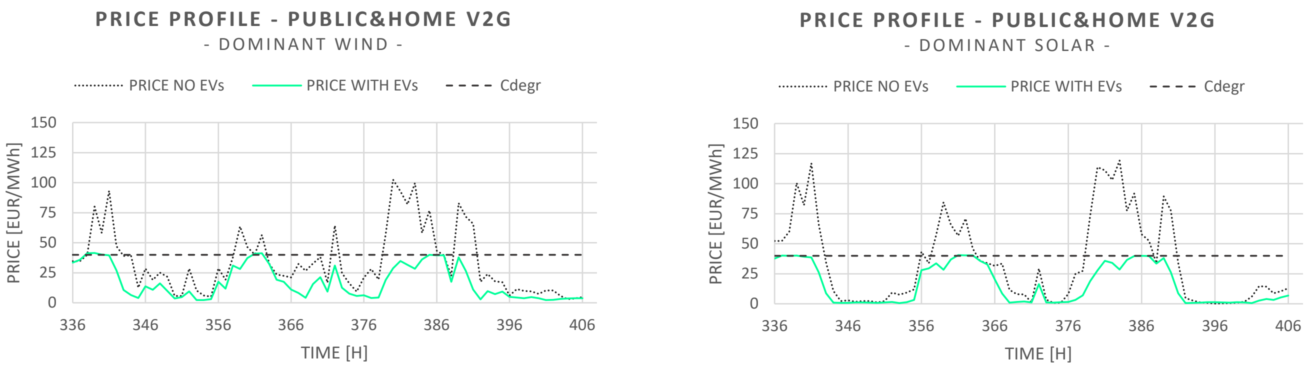


Figure 7.5 Price profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) for public&home charging with V2G. This includes the base case with no EVs, the price with inflation due to EV demand and battery degradation cost C_{degr}, indicated by the dotted line.

Residual demand

Residual demand profile

The results presented in figure 7.2 to 7.4 show stepwise the effects of adding control, public charging stations and V2G capabilities on the residual demand profile. This will be discussed in the following paragraphs.

The major takeaway from the residual demand profile for the dominant wind scenario and the dominant solar scenario for only home charging, presented in figure 7.2a and 7.2b respectively, is that the large peaks during the evenings can be avoided through controlled charging. This implies that residual demand for controlled charging is much smaller than uncontrolled charging in the evenings. This is reversed during the night and early morning where residual demand for controlled charging is larger than for uncontrolled charging. This shows the considerable effect of postponing home arrival charging by directing EV demand away from the early evening and towards nighttime.

For the dominant solar scenario, the aforementioned *Duck Curve* (page 6) can be identified in figure 7.2b through both the evening peak and the valley during daytime, leading to very large ramps. These can be as steep as a 200 MW increase over a time period of just several hours. Figure 7.3 shows the effect of adding public charging in which these evening peaks are reduced, and in the case of dominant solar these valleys are filled.

Addding V2G to the public charging cases shows peak reductions through energy arbitrage. And although this may not occur very frequently, it still represents a very significant 30 MW residual peak reduction for dominant wind and even 50 MW for dominant solar.

Although EVs were able to significantly reduce positive peaks and fill valleys by shifting energy, the residual demand profile still showed a cyclical day-to-day trend. This indicates that despite all personal vehicles being electric and capable of performing V2G functions, EVs alone do not flatten the residual demand profile completely by acting as storage. Obviously, this is technically possible, but due to the battery degradation costs implemented in the model, this is shown not to be done, since this is not economically attractive. This explains the limit around 55 MW seen as the maximum for the periods of high residual demand.

This can be concluded when comparing figure 7.4 and 7.5. Note that the flattened residual demand sections correspond directly to periods of an electricity price with no EVs that exceeds the battery degradation cost. These are thus the periods in which it is attractive for the vehicles to supply power back into the grid. Through the charging cost optimisation, which is run one EV at a time, each next EVs will do so until the dynamic electricity price is lowered to the benchmark price of battery degradation cost.

--

The effect on the residual demand duration curve will be presented on the following two pages and will be discussed in the following section.

G4V

Residual demand duration curve

The effect of EV charging on the residual demand duration curve for the two G4V scenarios is shown here. Three comparisons are made, the first depicted in figure 7.6 shows the impact of controlled charging for an only home charging case. The second, depicted in figure 7.7, shows the impact of controlled charging for a public&home charging case. Thirdly, in figure 7.8 the load duration curves are depicted for only home versus public&home controlled charging.

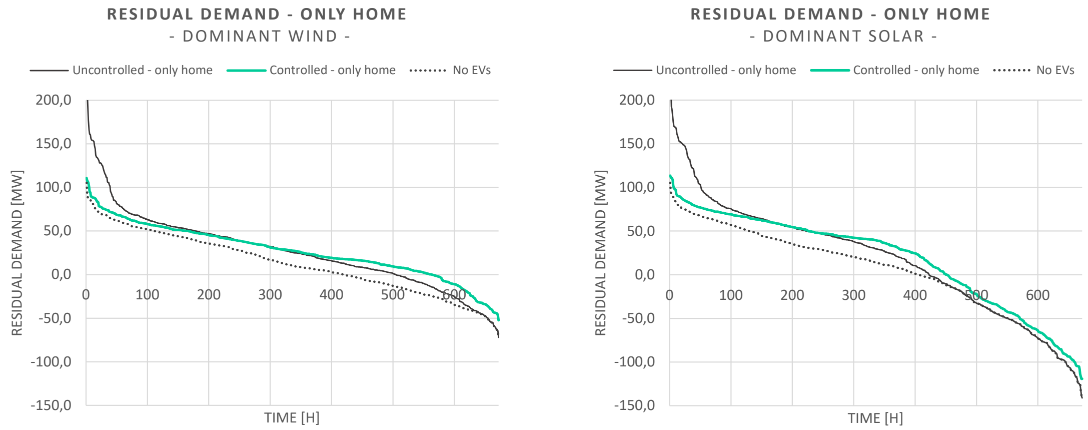


Figure 7.6 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for the case of only home charging, controlled vs. uncontrolled, and the base case with no EVs.

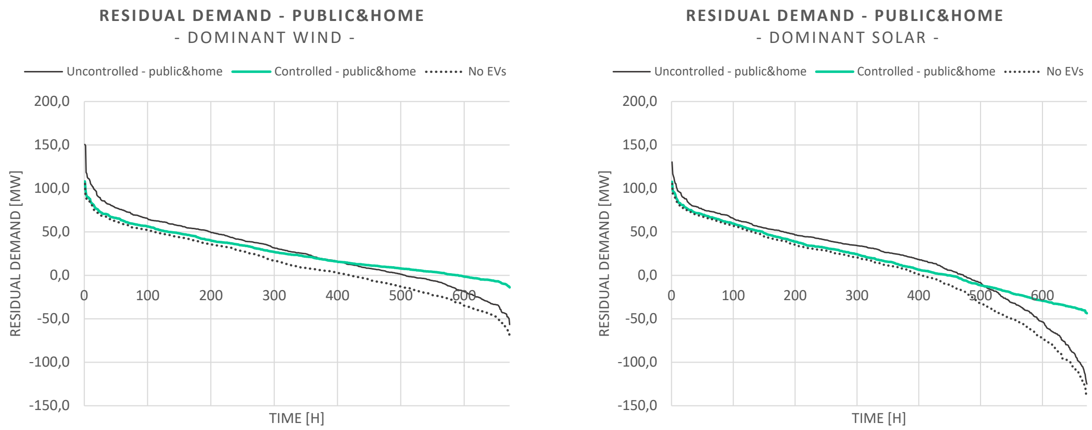


Figure 7.7 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for public&home charging, controlled vs. uncontrolled, and the base case with no EVs.

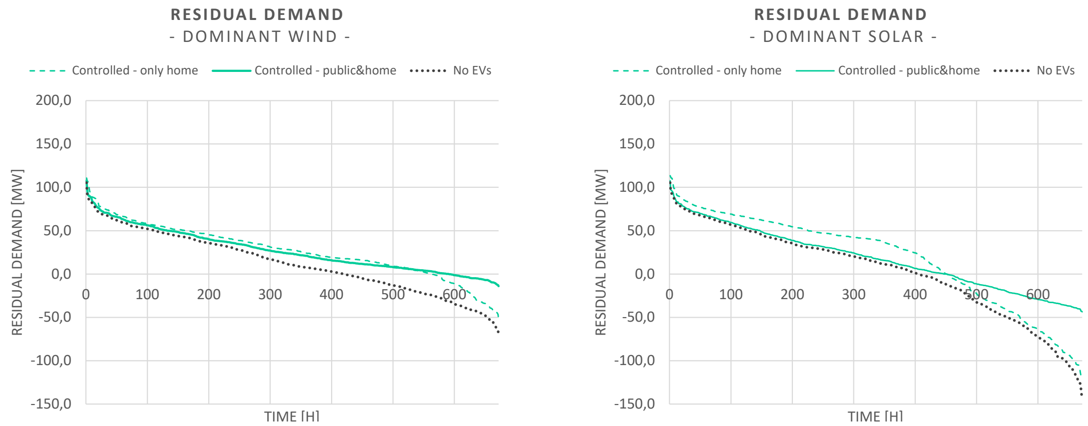


Figure 7.8 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for controlled charging, only home vs. public&home, and the base case with no EVs.

V2G

Residual demand duration curve

The effect of EV charging on residual demand duration curve for the two V2G scenarios is shown here. Again, three comparisons are made. Firstly, in figure 7.9 shows the impact of controlled charging for an only home charging case. The second, depicted in figure 7.10, shows the impact of controlled charging for a public&home charging case. And thirdly, in figure 7.11 the load duration curves are depicted for only home versus public&home controlled charging.

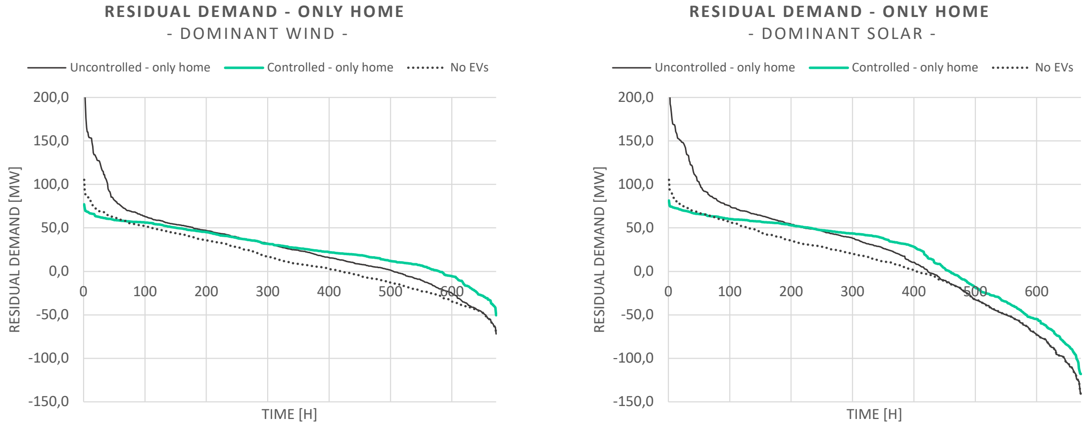


Figure 7.9 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for only home charging, controlled V2G vs. uncontrolled, and the base case with no EVs.

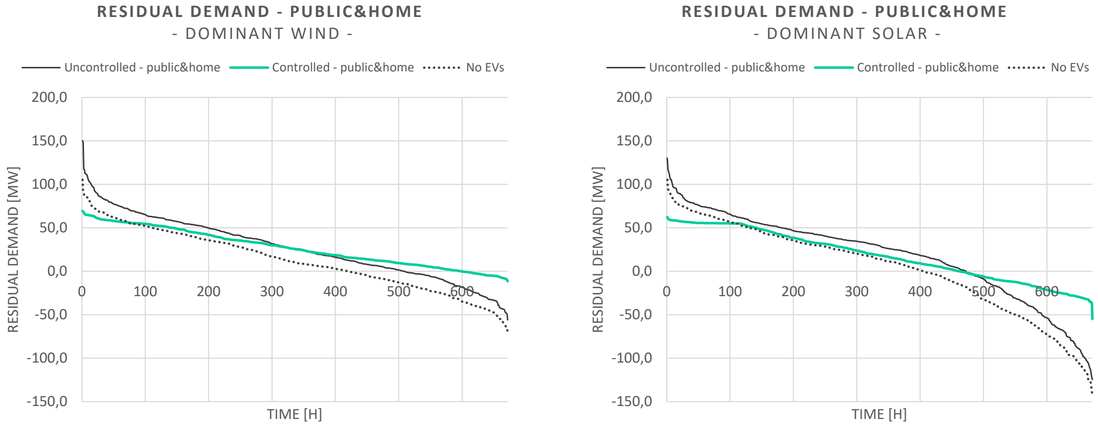


Figure 7.10 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for public&home charging, controlled V2G vs. uncontrolled, and the base case with no EVs.

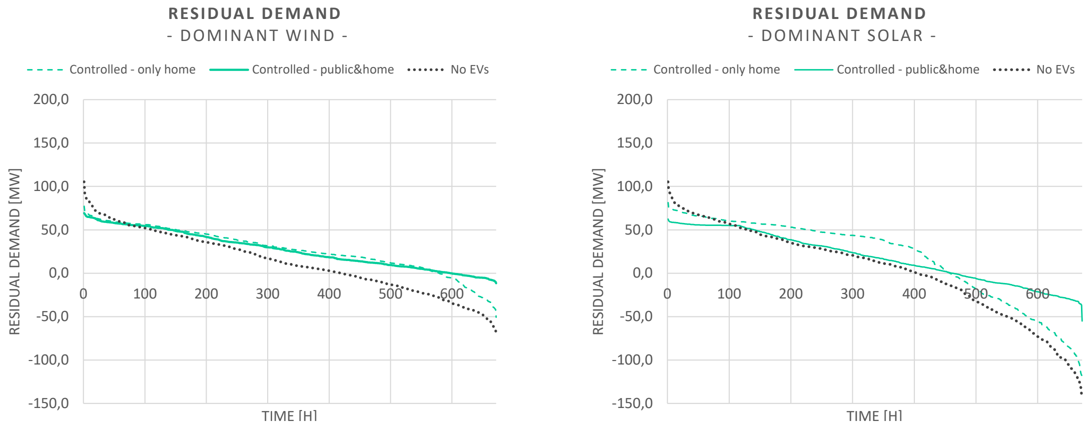


Figure 7.11 Residual demand load duration curves for the dominant wind scenario (a) and the dominant solar scenario (b) for controlled V2G charging, only home vs. public&home, and the base case with no EVs.

Residual demand

Residual demand duration curve

The general effect of EV charging shown in figures 7.6 until 7.8, for both controlled and uncontrolled charging is that the load duration curve is shifted up compared to the situation with no EVs. In other words, more residual demand is created and less energy is curtailed. The extent to which is done depends on the implemented charging infrastructure and control scenario.

Adding controlled charging changes the outline of the curve by reducing both positive and negative residual demand at the same time, flattening the load duration curve. This is a logical result as the total energy demand of the vehicles remains the same but is shifted to hours where there is curtailment. This is the aim of demand response.

What can be seen from the results of the dominant wind power scenario in figure 7.6a and 7.7a, is that a significant reduction of peak residual load is possible through the implementation of controlled charging. Note that this is the low power scenario where the moment and magnitude of power with which the vehicles are charged is optimised. Moreover, it is clear from the results that the addition of public charging stations has a positive effect on the load duration curve of most notably the uncontrolled scenarios in the form of a very large reduction of the peak residual power demand. This reaches 200 MW in the only home scenario in figure 7.4a and is reduced to roughly 150 MW in the public&home scenario in figure 7.7a. Both observations show the impact of the addition of public charging stations and adding controlled charging on the residual demand duration curve. When the addition of public charging is compared separately for both controlled cases in figure 7.8a, it can be seen that in both control cases the EVs are very effective at decreasing the curtailed energy, but including public charging allows for a further reduction of curtailed power on the far right of the curve.

A similar effect is shown for the cases from the dominant solar scenario in figure 7.6b, 7.7b and 7.8b. However, the original amount of curtailed power in the no EV base case (0) is higher than in the dominant wind scenario, 24% of system energy, compared to 16%, respectively. This is due to the fact that solar power is limited to the daytime hours and thus will create a peak of curtailed power around midday, whereas wind power is spread throughout the entire day and will thus have relatively less curtailment.

This leads to the result that the positive side of the controlled residual demand load duration curve for controlled public&home charging, depicted in figure 7.8b, is almost equal to the base case with no EVs. This indicates that the EVs are very well able to shift their demand to times of curtailed energy. Causing almost no increase of the positive residual demand part and so negligible increase of dispatchable generation. Only home controlled charging on the other hand, also depicted in figure 7.8b, is far less effective at achieving this goal. A small decrease of curtailed power is possible, but there still remains a spread increase in positive residual demand compared to the no EVs case. This shows the need of public charging implementation to achieve the reductions in curtailed energy for the dominant solar scenario.

For the two V2G scenarios similar results are presented in figures 7.9 until 7.11. However, for the case of controlled public&home charging in figure 7.10a and 7.10b, the first part of the positive side of the residual load duration curve is lower than the base case without EVs. This shows the effect of bi-directional EV charging where the vehicles supply power back into the grid at peak residual demand. In doing so, they effectively take over the role of conventional peak power production and decrease positive residual demand peak considerably. This impact is most significant for the public&home charging cases in combination with the dominant solar scenario, since there the EVs are able to benefit from the large daytime curtailment peak, by taking up excess energy and supplying it back later, during peak hours. For the other cases this reduction is less, but still very significant, as peak power is reduced from approx. 110 MW to 70 MW.

The effects of the 4 scenarios and 6 cases on the other technical indicators will be presented here. This entails an overview of amount of curtailed energy (as share of total system energy), share of EV demand from curtailed energy, and ultimately, the net power generation emissions. On the following pages, these results are presented in figures 7.12-7.17. The impact on curtailed energy will be discussed in the following section. The other impact on the other indicators will be discussed in the following sections.

Curtailed energy

What is visible from the results for the dominant wind power scenario in figure 7.12a is that the addition of public charging stations allows reductions in curtailed energy for both the controlled and uncontrolled scenarios (as was visible from the load duration curve). Furthermore, no significant decrease is visible through the move to high power, indicating that for the modelled EVs a low power infrastructure does not form a constraint in their ability to take up curtailed power. For the dominant solar power scenario, the curtailed energy amounts in figure 7.12b follow the same trend as for the dominant wind scenario in figure 7.12a, but here a second decrease is visible for the cases with high power.

It is clear that the cases with controlled charging, public&home infrastructure and high power level perform best at reducing the curtailment of electricity shown in figure 7.12a and 7.12b. This can be understood through 1) the ability to charge during daytime through the addition of public charging infrastructure and thus the ability take up excess (solar) power, 2) the change to a high power level that allows for a larger maximum power flow to the vehicles and thus a small increase ability to take up otherwise curtailed energy. This last factor is of less importance for the six cases analyzed here since the amount of electric vehicles is maximised to 50,000. If a smaller number were to be used, the influence of these factors will become larger due to the fact that the curtailed power needs to be divided over fewer cars and thus the maximum charging power constraint per vehicle will be reached sooner.

The differences between the curtailed energy in the various cases are larger in the dominant solar scenario in figure 7.12b. Most notably for the controlled cases where the addition of public charging stations creates a significant difference in curtailed energy, compared to negligible differences for the dominant wind scenario cases. Although generally, the addition of controlled charging and public charging stations roughly halves the amount of curtailed energy compared to the situation with no EVs: 16% to 8% for dominant wind and 24% to 13% for dominant solar.

When the results for the load duration curves in figure 7.6 and 7.7 are compared to the results for curtailed energy in figure 7.12, it seems that the reductions in curtailed energy values are smaller than those presented in the load duration curve. Recall that the area between the negative part of the curve of the residual load duration curve and the x-axis represents moments of excess generation and thus result in curtailment of energy. This is a result of the fact that the conventional generators have a non-zero minimum power output and (one of) these need(s) to run continuously to provide ample spinning reserve. The consequence is that even when there is excess renewable energy, (one of) these turbines will run at minimum level and thus will generate power that will be curtailed. This implies a certain base level of curtailed power that cannot be reduced by controlled EV charging.

For the two V2G scenarios, the amount of curtailed energy reductions shown in figure 7.15 are similar to those presented for the two G4V scenarios. Generally, it can be seen that the addition of V2G allows for reductions of 1 percentage point for dominant wind and 2 percentage points for dominant solar, compared to the values presented for G4V. However, for V2G the differences between the various cases are slightly smaller. The 12% curtailed energy as is visible for the controlled high power public&home case is the minimum possible amount, since the total EV demand equals 12% of system energy for the dominant solar scenario. This entails that the EVs take all of their energy demand from otherwise curtailed energy. This will be discussed in the following section.

G4V

Curtailed energy

The extent to which curtailed energy is affected by the six EV charging cases was examined. The results are shown in figure 7.12.

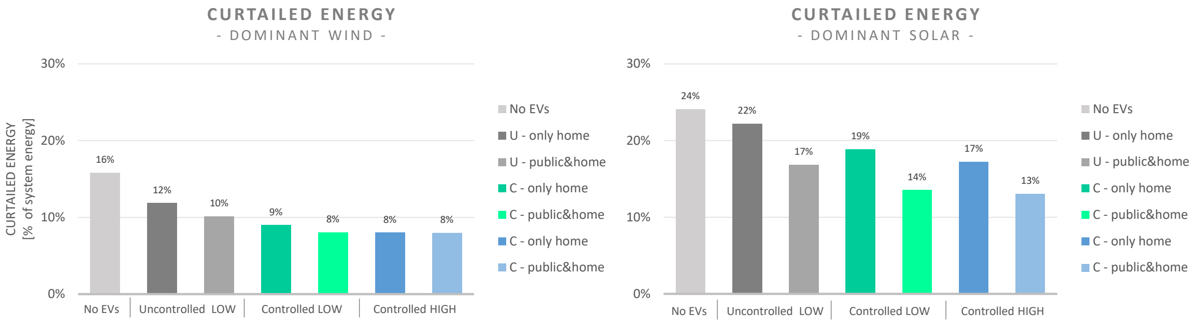


Figure 7.12 Curtailed energy for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled, and the base case with no EVs.

The next key indicator is the share of EV demand from curtailed energy. This is presented in figure 7.13 for the six cases.

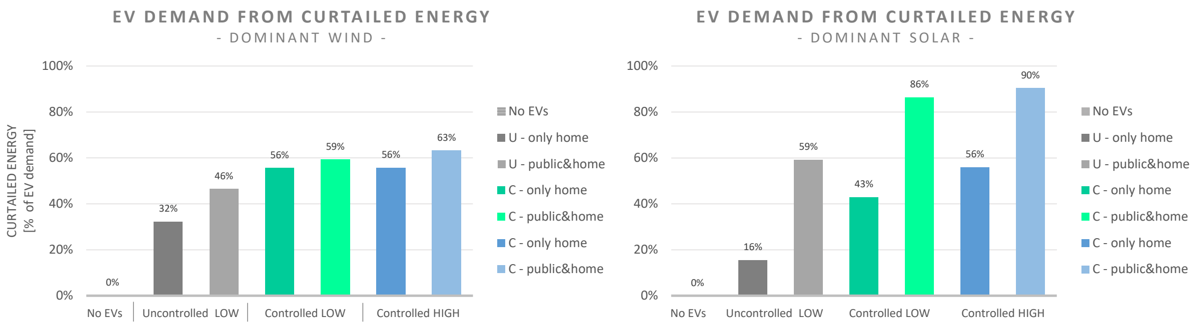


Figure 7.13 Curtailed energy used for EV charging for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled, and the base case with no EVs.

Emissions

The effect on net power generation emissions is presented in figure 7.14.

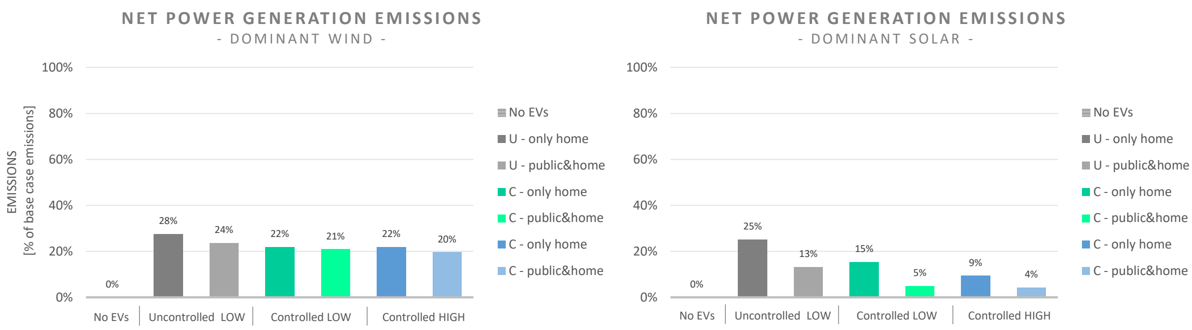


Figure 7.14 Net power generation emissions for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled. The base case with no EVs is effectively zero.

V2G

Curtailed energy

The extent to which curtailed energy is affected by the six EV charging cases was examined. The results are shown in figure 7.15

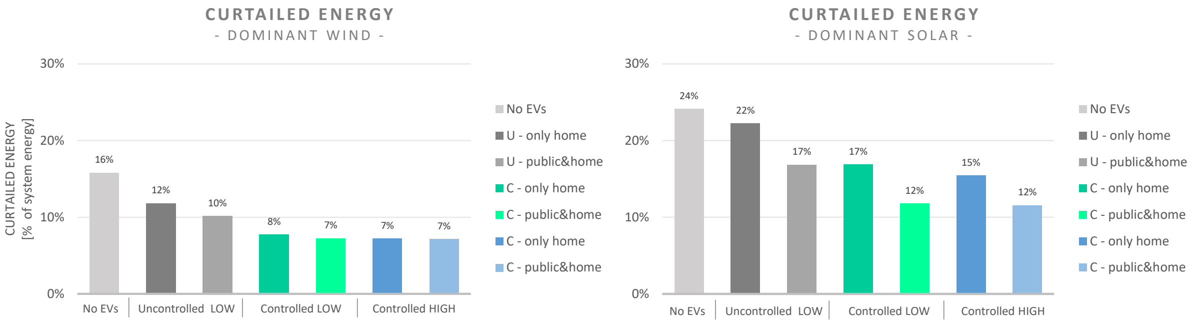


Figure 7.15 Curtailed energy for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled, and the base case with no EVs.

The next key indicator is the share of EV demand from curtailed energy. This is presented in figure 7.16 for the six cases.

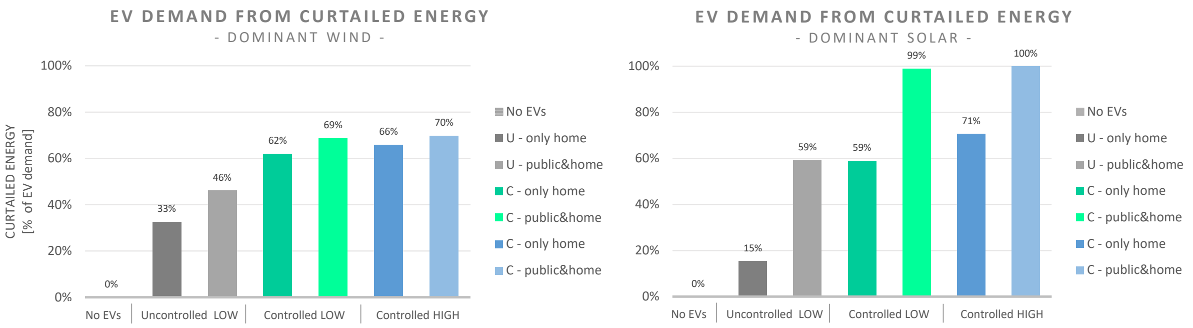


Figure 7.16 Curtailed energy used for EV charging for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled, and the base case with no EVs.

Emissions

The effect on net power generation emissions is presented in figure 7.17.

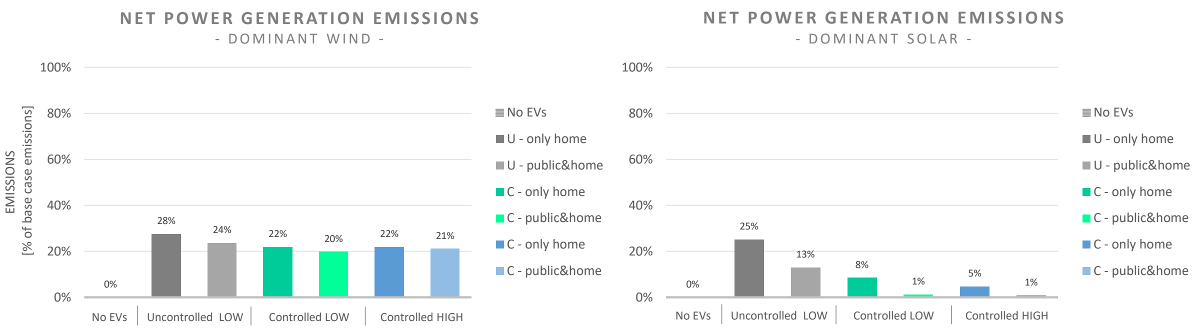


Figure 7.17 Net power generation emissions for the dominant wind scenario (a) and the dominant solar scenario (b) for the six cases, controlled and uncontrolled. The base case with no EVs is effectively zero.

Share of EV demand from curtailed energy

The shares of EV demand from curtailed energy in the dominant wind scenario in figure 7.13a show a moderate increase in uptake of curtailed energy for the addition of public charging stations. The results for the share of EV demand from curtailed energy for the dominant solar scenario in figure 7.13b show a more distinct difference for both controlled and uncontrolled charging. For the uncontrolled cases the share more than tripled. For the controlled low power cases the share doubled. The differences between the six cases highlight once more the effects of adding control, the addition of public charging and the move to high power.

The highest value of 90% shows that in these simulated scenarios, almost all of the energy needed to charge the vehicles could originate from otherwise curtailed energy. Thus increasing the utilisation of renewable energy to a large extent. The remaining share of EV demand originates from the power mix and thus from both renewable and conventional power sources. Since it cannot be said from which source energy is curtailed, it is also not possible to say exactly from which source the remaining energy used to charge the vehicles comes.

For the V2G cases, this percentage grows to 100% for the dominant solar scenario combined with high power public&home charging infrastructure. A similar value of 98% is found for low power infrastructure. This shows the marginal increase in benefit from a high power infrastructure.

Emissions

Recall that the reduction in emissions from all 50,000 vehicles was 230 ktonCO$_2$-eq/year and power generation emissions were 155 ktonCO$_2$-eq/year and 165 ktonCO$_2$-eq per year for the dominant wind and solar scenarios. So based on the results shown in figure 7.14 it can be said that the combined emissions of power generation and vehicles together are reduced signifcantly for all cases.

The net emissions increases for these cases range between 20% and 28% for the case of the dominant wind scenario. For the dominant solar scenario, a maximum 25% and a minimum of 4% are found. These are modest increases, and thus show the impact of changing from diesel or gasoline fuel to mostly renewable energy to power these vehicles. And more importantly, that this reduction of vehicle emissions can be exploited almost completely for the cases with dominant solar power and public charging where this is accompanied by a very small (5-6%) increase in power generation emissions.

A similar trend to the reduction of curtailed energy is visible for the reductions in emissions. This is a natural extension of the previously stated observations: the emissions are reduced through the addition of public charging stations, the move to flexible charging power and the move to high power.

In the case of V2G, presented in figure 7.17, the net power generation emissions can almost be reduced to zero at a 1% net increase, and are thus approximately equal to the base case with no EVs. This only holds true for the for the dominant solar scenario with public&home charging. This shows the potential of the combination between V2G capabilities and public charging infrastructure. For the dominant wind cases the effect is much smaller, and the lowest value was found to be 20%. Even smaller differences were found between the different cases, indicating that the effect of adding controlled charging or public charging infrastructure is far less in the dominant wind scenario with V2G.

The effects of the 4 scenarios and 6 cases on the disptach profile will be presented here. The results are presented on the following two pages and are discussed below.

Dispatch profile

Only home

The dispatch profiles for controlled EV charging in both the dominant wind and the dominant solar scenario, depicted in figure 7.19, show that with only home charging the EVs are in fact able to partly induce their demand at the times of curtailed energy. In the dominant wind scenario, there is more curtailment in the early evening and the EVs are therefore able to make use of this, causing a limited increase in conventional generation. For dominant solar, this is not the case, and thus a larger increase in conventional generation is shown.

Contrastingly, for uncontrolled charging in figure 7.18, EV demand does not correspond to peaks in renewable generation. EV demand, in the form of peaks, is introduced at moments that correspond to the arrival times of home-work travel. For the both scenarios, these peaks do not correspond to renewable energy generation, and thus see a sharp increase in power generation from the peak power units.

An interesting observation is that although controlled, in the case of the dominant wind scenario depicted in figure 7.19a, not all EV demand is allocated to moments of energy surplus. Part of EV demand is, but another part is introduced around the end of the afternoon, showing the need for an extra charge to be able to make the return trip and the lack of the possibility to do so during the following hours since the vehicle is on the go.

Adding V2G capability, shown in figure 7.20, makes it possible to reduce power generation demand from conventional sources during moments of peak residual demand. This is visible in the early morning on the second and third day, before solar power starts producing.

Public&home

Adding public&home charging infrastructure then changes the dispatch profile for uncontrolled charging, shown in figure 7.21, most notably through the peaks in the morning that are the result of people arriving at work and plugging in their vehicles to charge. Thus causing significant increases in reciprocating and peak generation for the dominant wind scenario. For the dominant solar scenario on the other hand, it shows that these peaks do occasionally overlap, as shown in the first two days, and thus do not require this output of conventional power.

This can be compared to the situation with controlled charging depicted in figure 7.22. Here it is clear that the EVs shift their demand to times of curtailment during midday. Furthermore, the results showed that EV demand followed a similar pattern to the combined total generation profile. This is a natural result of the structure of the price signal, where an increase in renewable energy surplus is matched by a low price and thus the trigger to start charging the EVs.

The cases with vehicle-to-grid capabilities in figure 7.23 show similar results, but when comparing these plots to those without V2G in figure 7.21, it can be seen that to be able to supply this power back to the grid and still ensure enough capacity to perform the daily driving routine, the EVs take up more power during the daytime peak.

Only home

Power dispatch profile

In this section, the effect of the EV charging on the power dispatch profile for both G4V scenarios is presented for only home charging. This is done for the dominant solar and the dominant wind scenario. Firstly for the situation of uncontrolled charging in figure 7.18, secondly for controlled charging in figure 7.19 and thirdly for controlled V2G charging in figure 7.20.

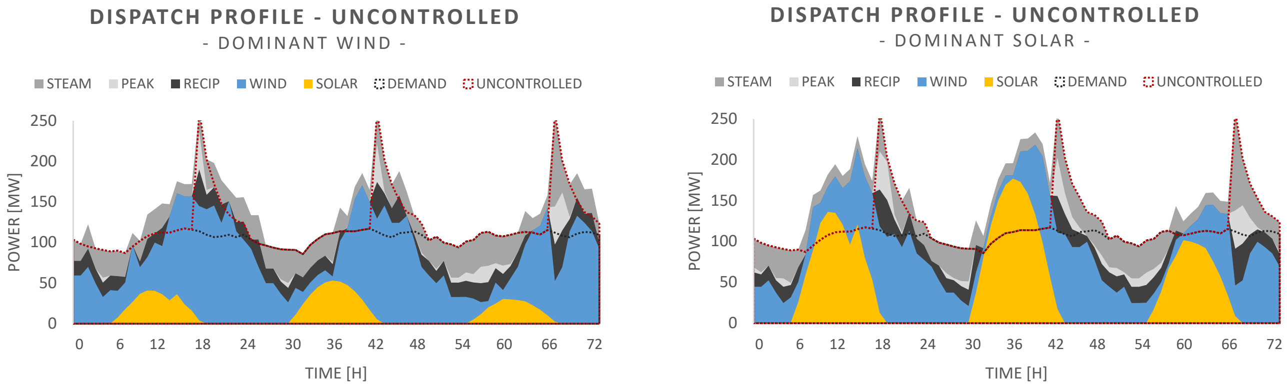


Figure 7.18 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the uncontrolled only home charging case.

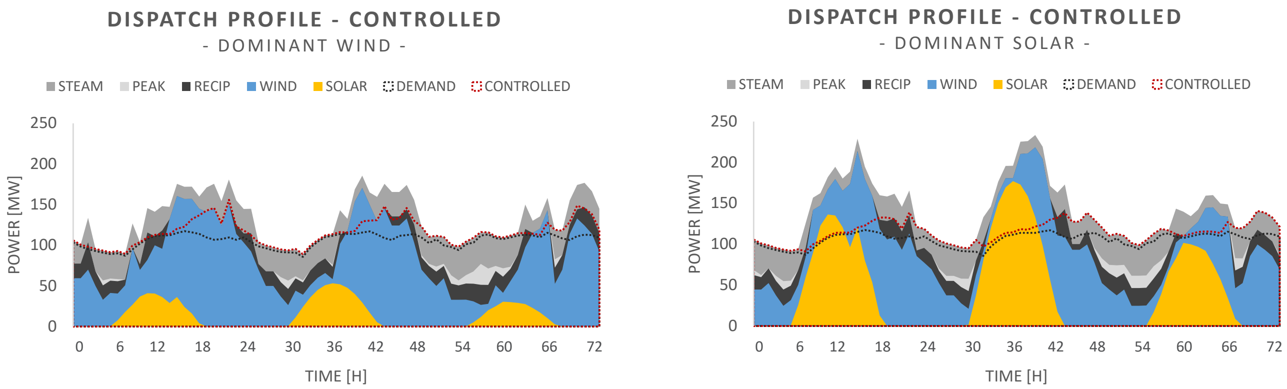


Figure 7.19 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the controlled only home charging case.

.

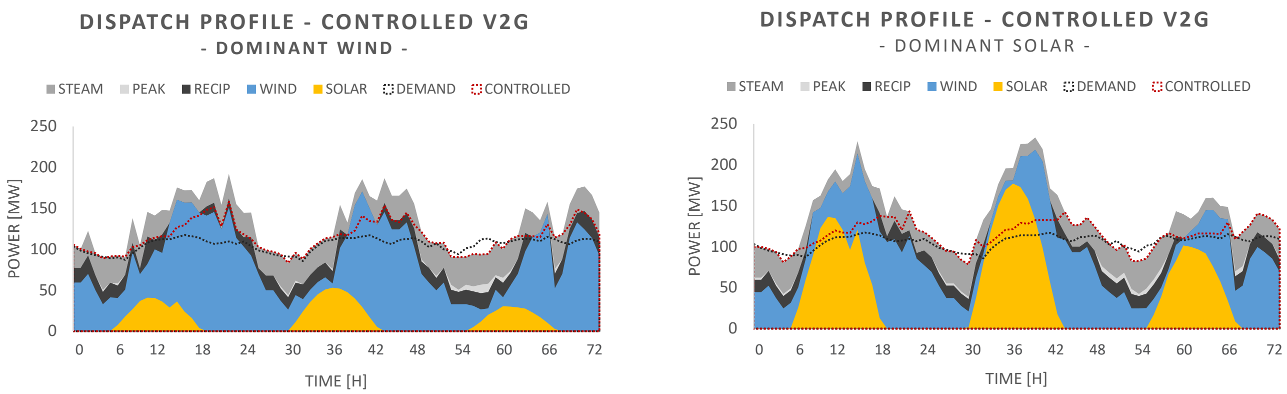


Figure 7.20 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the controlled only home charging case with V2G.

Public&home

Power dispatch profile

In this section, the effect of the EV charging on the power dispatch profile for both G4V scenarios is presented for public&home charging. This is done for the dominant solar and the dominant wind scenario. Firstly for the situation of uncontrolled charging in figure 7.21, secondly for controlled charging in figure 7.22 and thirdly for controlled V2G charging in figure 7.23.

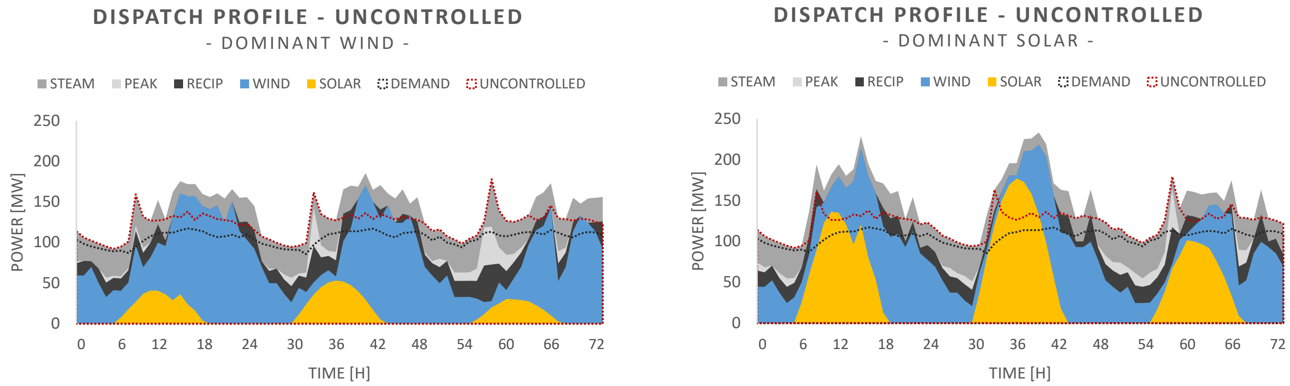


Figure 7.21 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the uncontrolled public&home charging case.

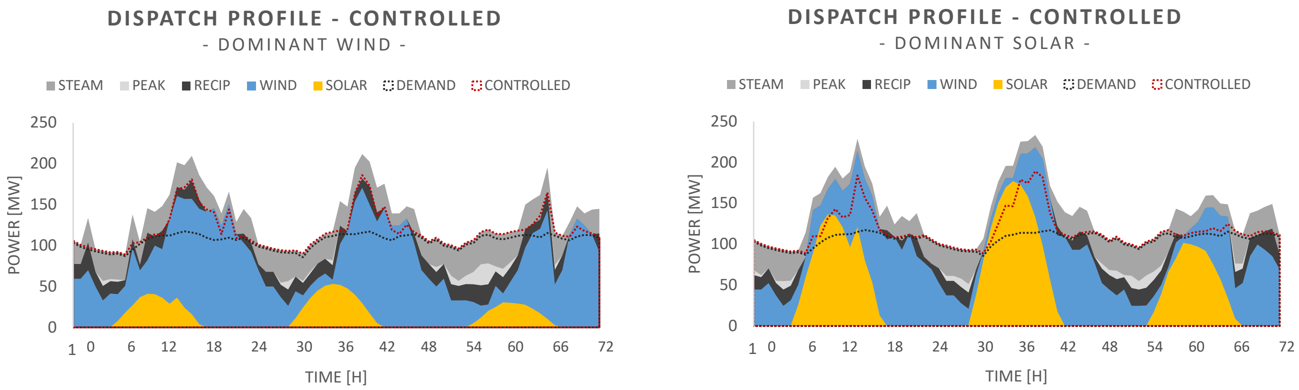


Figure 7.22 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the controlled public&home charging case.

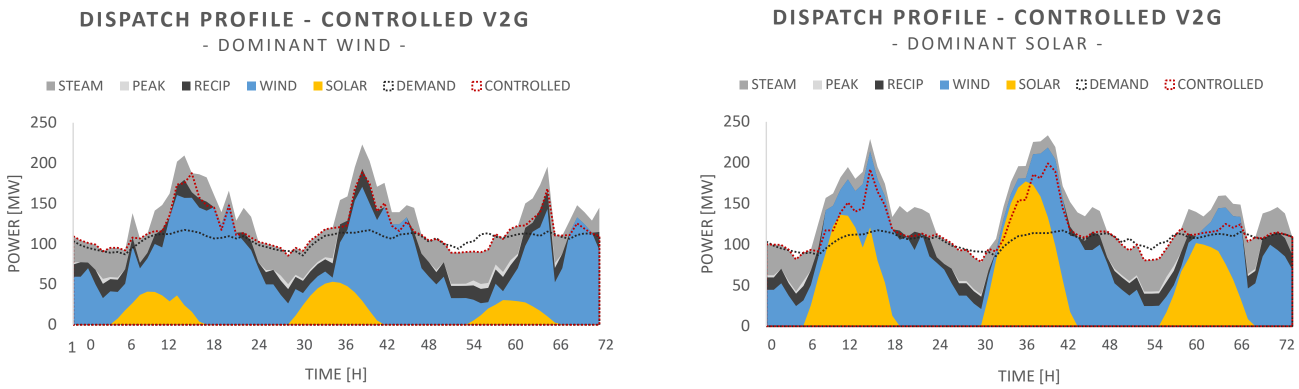


Figure 7.23 Dispatch profile for a three day period for the dominant wind scenario (a) and the dominant solar scenario (b) showing electricity generation for the controlled public&home charging case with V2G.

7.2 Economic potential

In this section, the effect of the 4 scenarios and 6 cases on the key economic indicators will be presented. This entails an overview of investment and periodic cost of charging infrastructure, system levelised cost of electricity (sLCOE) and ultimately, the total system levelised cost (sLC). This last indicator combines the charging infrastructure costs with the sLCOE to give an estimation of the economic potential of the different charging cases within different scenarios. On the following pages, these cost data are presented in figures 7.24-7.29.

The *calculated* present-day (2015) levelised cost of electricity based on HFO generation is 158 €/MWh.

Charging infrastructure costs

From figure 7.24a and 7.24b it can be seen that for one-directional charging infrastructure (G4V) the additional cost of public charging is 125 M€ and the addition of control constitutes an investment of 13 M€. Moving to a high power infrastructure almost doubles these costs for public&home charging at 288 M€, whereas only home charging with a high power infrastructure can be implemented for 63 M€. A similar picture is visible for the periodic charging infrastructure costs. Here the additional cost of public charging infrastructure are an annual 10 M€ and adding control entails an additional 3 M€ per year.

Power generation costs

Generally it can be concluded that power generation costs are found to be lower than the calculated current sLCOE based on HFO, for all cases and scenarios. Regarding the system levelised cost of power generation (sLCOE), depicted in figure 7.25, it is clear that adding uncontrolled electric vehicle charging increases system generation costs considerably. This can be understood through the increase in demand and thus an increase in running cost for conventional power generation. Levelised costs are reduced for the addition both control and public charging infrastructure. The results differ between the dominant wind and the dominant solar scenario.

The effect of moving to a high power infrastructure is evident for the only home case within the dominant solar scenario, but is insignificant for the dominant wind scenario and the public&home case for dominant solar. These sLCOE figures follow a similar trend to the reductions in curtailed energy. A logical result since these are directly linked through the additional need for conventional power generation. Interesting to note here though, is the fact that sLCOE shows values lower than the base case without EVs for the dominant solar scenario, but not for the dominant wind scenario.

Total system costs

The economic theory assumed here is that a lower sLC, compared to sLC of the case of uncontrolled charging with only home charging, provides economic incentive to install these levels of charging infrastructure. In other words, if the reduction in power generation cost is larger than the additional cost of control and infrastructure, there is a net economic benefit. This is thus a measure for the financial incentive of the addition of public charging stations as well as the implementation of controlled charging. Therefore, the sLC of uncontrolled only home charging is shown as benchmark in the sLC data shown in figures 7.26 and 7.29, indicated by the dotted line.

When both costs are combined into the system levelised cost (sLC), depicted in figure 7.26, and compared to the benchmark of uncontrolled only home charging, the following is visible. For the dominant wind scenario, the addition of control for the only home cases provides an economic incentive to invest in this type of infrastructure. Implementation of public charging stations is never attractive for dominant wind as levelised system cost are structurally higher than those of uncontrolled only home charging: the levelised cost for this public infrastructure do not outweigh the relatively small reductions in sLCOE. It can be seen that infrastructure and control implementation cost need to drop considerably, to approximately 1/3 of their cost, to reach the benchmark cost of uncontrolled only home charging. Even when regarding future cost reductions, this is deemed unrealistic.

For the dominant solar scenario all cases do provide economic incentive to invest both in control and public charging infrastructure. Interestingly, the sLC for only home and public&home in the low power case, are comparable. This shows that the steep cost of public charging are justified by a significant reduction in power generation cost.

This is not shown for the high power infrastructure, where the additional cost for public charging infrastructure are significantly higher than those in the low power case and cannot be compensated by power generation cost reduction. Although, here the cost of charging infrastructure is overestimated. Namely, a high power infrastructure means charge times can be cut shorter and therefore less stations are needed.

The addition of vehicle-to-grid capabilities increase the charging infrastructure investment costs considerably, but periodic cost remain the same. Naturally, these seemingly low costs are because of the fact that battery degradation cost are already accounted for in the model. For these cases with vehicle-to-grid technology, the individual results do not differ much to those presented for the G4V scenario: the results also follow the trend of the curtailed energy.

Comparing these results to the G4V scenario however, is interesting. It can be concluded that despite the added costs, the implementation of V2G technology proves to be cost effective for all cases for both scenarios. The addition of public charging infrastructure for dominant wind remains unattractive, regardless of including V2G.

Interestingly, it can be seen that for public&home charging, for both dominant wind and dominant solar, the extra cost of charging infrastructure are exactly compensated by the reductions in sLCOE. Thus showing that the value of adding V2G capabilities is equal to the cost of implementation.

G4V

Charging infrastructure costs

In this section, the estimated costs of the EV charging infrastructure will be presented for the six cases. The investment cost are shown in figure 7.24a and the periodic cost in figure 7.24b. Furthermore sLCOE is shown in figure 7.25 and sLC in figure 7.26 for the dominant wind scenario (a) and the dominant solar scenario (b). These were calculated using the cost calculation stated in section 5.7.

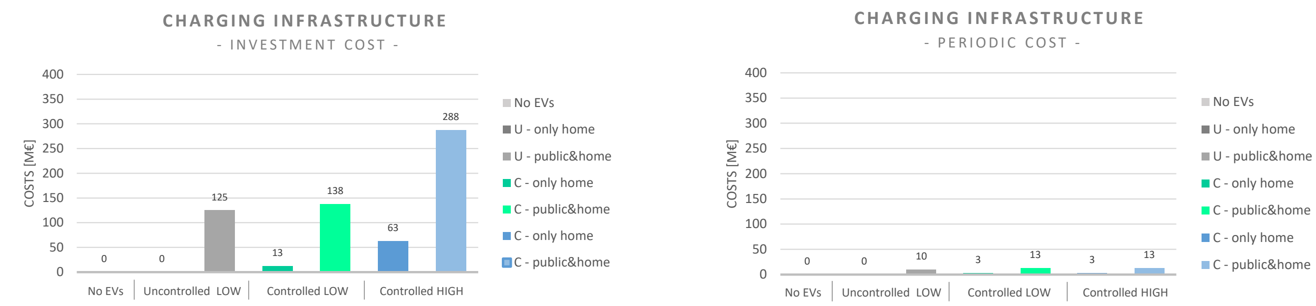


Figure 7.24 Costs of charging infrastructure for the G4V cases, presented as investment cost (a) and periodic cost (b).

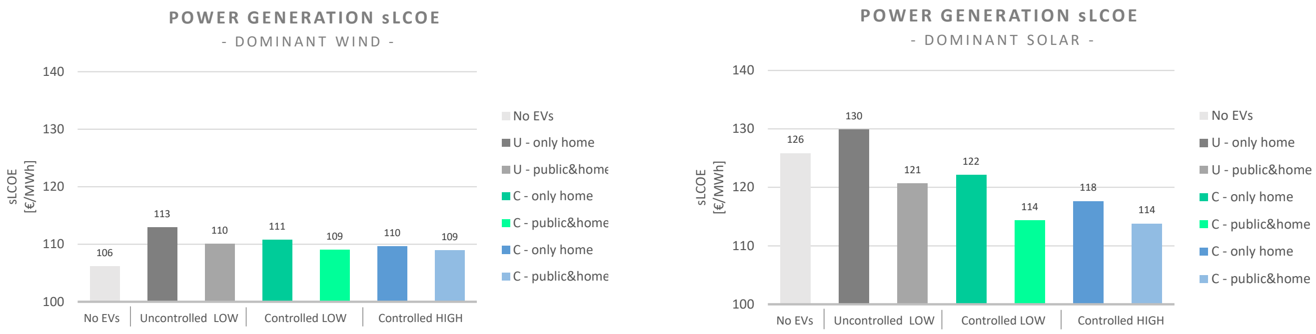


Figure 7.25 Power generation system levelised cost for the G4V cases in the dominant wind (a) and the dominant solar scenario (b).

The sLC values for the G4V cases presented in figure 7.26 show the added costs of charging infrastructure and control implementation, indicated by the diagonally shaded bar on top of the original sLCOE value, which was presented in figure 7.25 . Furthermore, a comparison is made to the benchmark value of uncontrolled only home charging, indicated by the dotted line. Recall that the costs of electric vehicles are not taken into account.

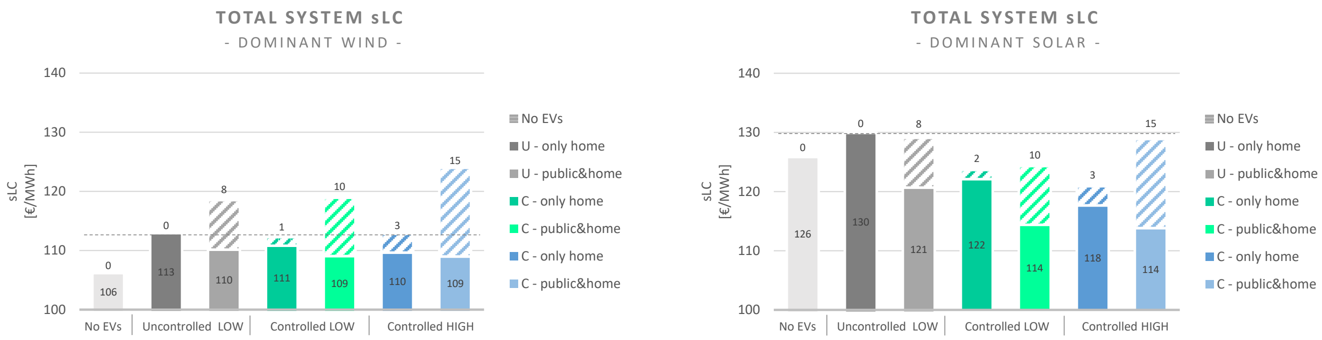


Figure 7.26 Total system levelised cost (sLC) for the G4V cases in the dominant wind scenario (a) and dominant solar scenario (b) with uncontrolled only home charging as benchmark, indicated by the dotted line.

V2G

Charging infrastructure costs

In this section, the estimated costs of the EV charging infrastructure will be presented for the six V2G cases. The investment cost are shown in figure 7.27a and the periodic cost in figure 7.27b. Furthermore sLCOE is shown in figure 7.28 and sLC in figure 7.29 for the dominant wind scenario (a) and the dominant solar scenario (b). These were calculated using the cost calculation stated in section 5.7.

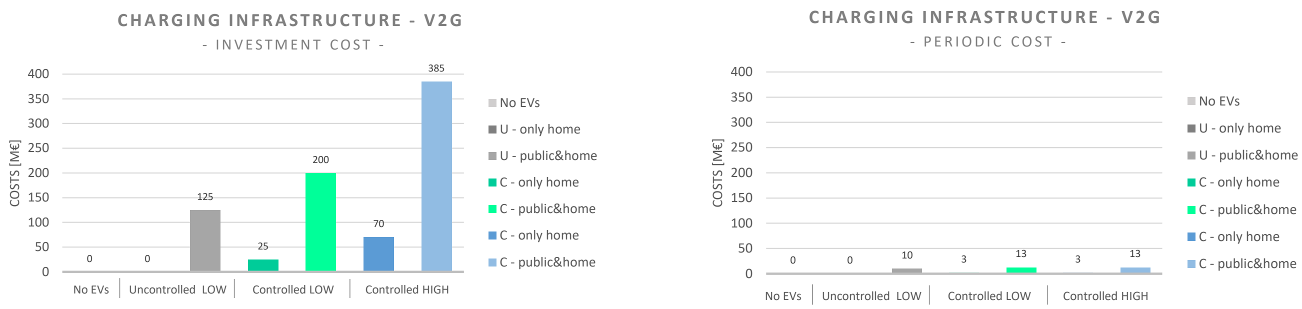


Figure 7.27 Costs of charging infrastructure for the V2G cases, presented as investment cost (a) and periodic cost (b).

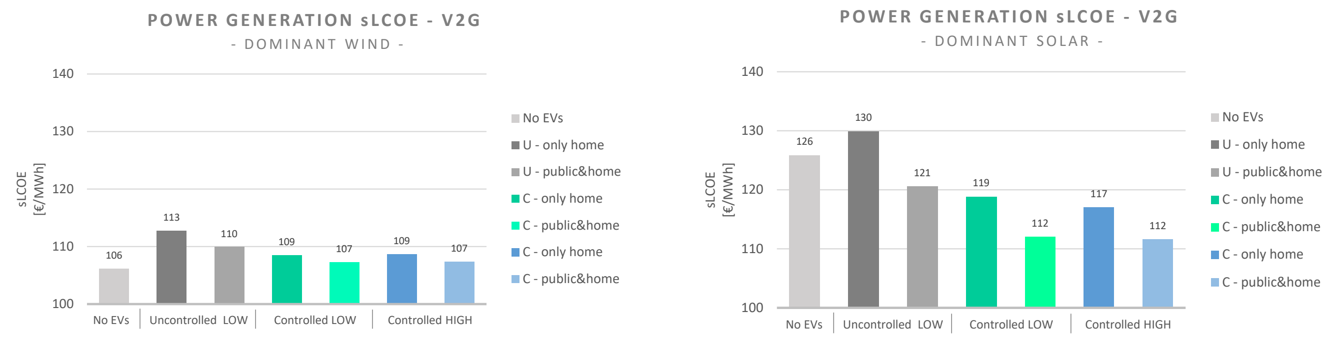


Figure 7.28 Power generation system levelised cost for the V2G cases in the dominant wind (a) and the dominant solar scenario (b).

The sLC values for the V2G cases presented in figure 7.29 show the added costs of charging infrastructure and control implementation, indicated by the diagonally shaded bar on top of the original sLCOE value, which was presented in figure 7.28 . Furthermore, a comparison is made to the benchmark value of uncontrolled only home charging, indicated by the dotted line. Recall again that the costs of electric vehicles are not taken into account.

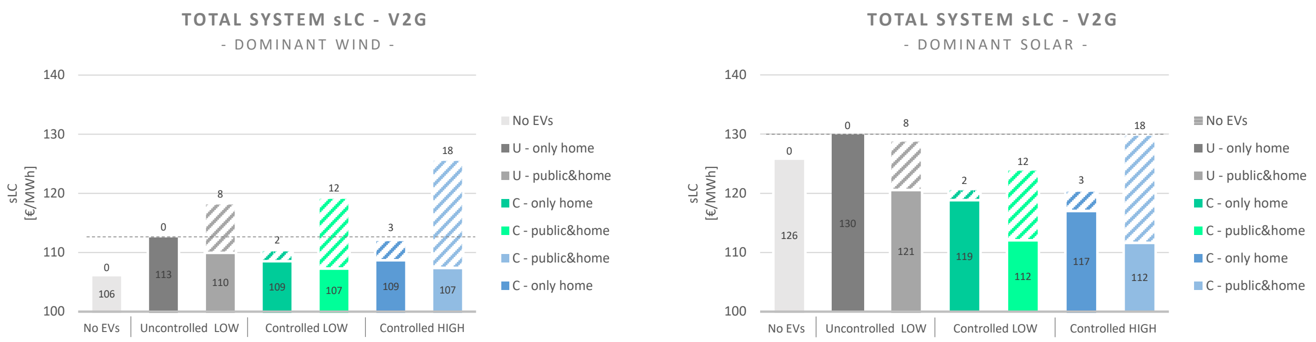


Figure 7.29 Total system levelised cost for the V2G cases in the dominant wind scenario (a) and dominant solar scenario (b) with uncontrolled only home charging as benchmark, indicated by the dotted line.

7.4 Sensitivity analysis

To be able to judge the influence some of the assumptions made in the modelling and cost calculations, a sensitivity analysis was performed. The dominant solar scenario with low power controlled public&home charging was taken as a reference case. The influence of several factors has been evaluated. These are summarised in table 7.4.

Table 7.4 Overview of factors investigated to evaluate model sensitivity to these assumptions.

Factor	**Description**
Reference case	*Dominant solar scenario with low power controlled public&home charging*
25,000 EVs	Half of the simulated amount of EVs
10 MW spinning reserve	Reduced spinning reserve requirement
HFO as fuel	Heavy fuel oil (HFO) as fuel, resulting in higher generator output minima
C_{degr} +50%, -50%	Influence of higher and lower battery degradation cost
Charge infra cost +25%, -25%	Influence of higher and lower future charging infrastructure cost

The argument behind these cases and the results showing their influence will be discussed in the next sections. The results are summarised in table 7.5 on the following page.

Amount of EVs

An amount of 25,000 EVs, half of what is used in this thesis, was analysed to see the effect of a smaller amount of EVs. It was found to result in 17% curtailed energy compared to 14% for the reference case of 50,000 EVs. However, if compared to the base case without EVs, where curtailed energy was 24% of system energy, it can be seen that with the first group of 25,000 EVs most of the reductions are made (7%p.), and the added 25,000 EVs contribute significantly less (3%p.). The results showed that 95% of EV demand originated from curtailed energy and net emissions were increased with 1% instead of 5%. So because of the smaller energy demand of the EVs and the fact that these EVs are able to take up a large share of curtailed energy, the conventional power generation and emissions only increased marginally. As a result, sLCOE was found to be slightly lower (112 EUR/MWh) than in the reference case, leading also to a lower sLC of 117 EUR/MWh. Note that the difference between both is only half of that in the reference case, since also half of the charging infrastructure costs are included. Uncontrolled only home charging for 25,000 was found to lead to a sLC of 118 EUR/MWh, showing that also for this amount of EVs, a margin exists between the benchmark and controlled public&home charging. Thus halving the fleet of EVs does not affect the main finding regarding the attractiveness to invest in control and public charging.

Spinning reserve

In a future power system, the maintained minimum spinning reserve may be lower due to smaller renewable generation units. Therefore the effect of a smaller spinning reserve constraint was analysed. It was found that the amount of curtailed energy is reduced to 10% of system energy, since there is less running load of gas-fueled turbines and engines required to maintain sufficient spinning reserve. Consequently, sLCOE and sLC were found to be lowered to 113 and 123 EUR/MWh, respectively. These are relatively small reductions and thus make the investigated cases slightly more economically attractive, but are not large enough to make investment in public infrastructure attractive for the dominant wind scenario.

Fuel type

Here the case is investigated that continues to implement the present-day use of heavy fuel oil for conventional generation. This influences the minimum power output of the generators and their emissions in the model. This resulted in more curtailed energy (13%) and higher net emissions increase (8%). Recall that these are net emissions compared to the case of no EVs, here with HFO-based generation, not to the reference case. Because of a lower fuel price, the sLCOE and sLC were found to be lowered. Due to the considerably higher minimum power outputs and the unchanged spinning reserve requirement, significantly more curtailment was found to occur. Thus making controlled EV charging mostly during midday more important.

The numerical results in the form of the influence on the key indicators are summarised in table 7.5

Table 7.5 Results of influence of investigated factors on key indicators used in this analysis.

Factor	Curtailed energy	EV demand from curtailed energy	Net emissions	sLCOE	sLC
No EVs	**24%**	**0%**	**0%**	**126**	**126**
Reference case	*14%*	*86%*	*5%*	*114*	*124*
25,000 EVs	17%	95%	1%	112	117
10 MW spinning reserve	12%	90%	3%	113	123
HFO as fuel	16%	87%	8%	97	107
C_{degr} +50%	16%	82%	6%	115	125
C_{degr} -50%,	13%	92%	4%	113	123

Battery degradation cost

The assumed degradation cost C_{degr} for battery cycling, when used for V2G purposes, is dependent on the conditions at which this happens and there are many uncertainties regarding this value. However, in this thesis a constant value has been applied, not linked to for example depth-of-discharge. Therefore the influence of a 50% lower and a 50% higher cost have been analysed. The results showed that for an increase in degradation cost, the vehicles took up less curtailed power and so the net emissions were increased. For reduced degradation cost, the opposite is visible. The differences for moving to lower degradation cost are proportionally larger, since there is a non-linear relation between these costs and the key indicators. Consequently, the sLCOE and sLC were also affected. However, the general conclusions of this thesis regarding the economic incentive to invest in controlled charging and public charging infrastructure, remain unchanged. These changes do not significantly change sLCOE and therefore a considerable margin to the benchmark of uncontrolled only home charging remains.

Charging infrastructure cost

Lastly, to see the influence on the economic comparison of a variation in charging infrastructure cost assumptions, two cases are analysed: one with a 25% higher cost, and one with 25% lower cost. The results are depicted in figure 7.30. Recall that the added costs of charging infrastructure and control implementation are indicated by the diagonally shaded bar on top of the sLCOE value, and a comparison is made to the benchmark value of uncontrolled only home charging, indicated by the dotted line. It can be seen that the general conclusions of this thesis regarding the economic incentive to invest in controlled charging and public charging infrastructure, do not change. Only for the case of a high power infrastructure the sLC are increased and thus exceed the benchmark of uncontrolled only home charging.

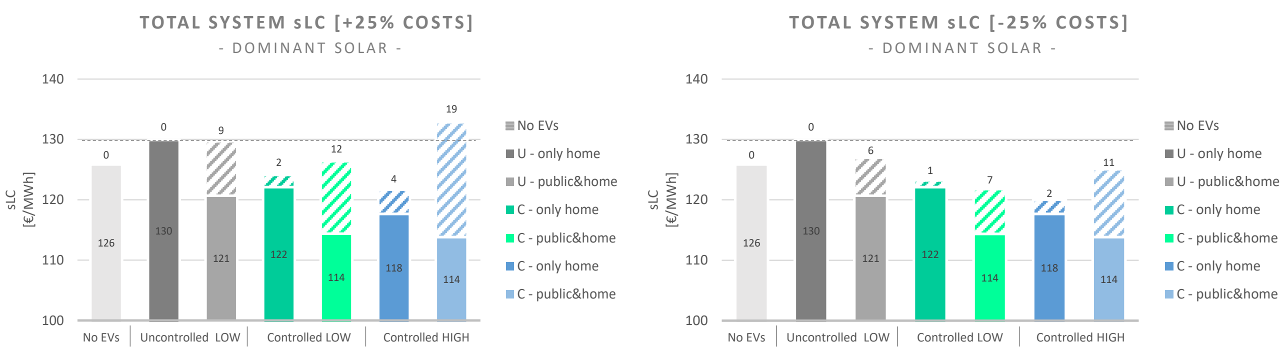


Figure 7.30 Results of influence of 25% higher (a) and 25% lower (b) charging infrastructure cost.

8. REFLECTION

8. REFLECTION

8.1 Comparison to literature

In this section, the results are compared to the main findings of the core papers discussed in section 3.2.

Diaz et al. [60] found significantly the greatest benefits when V2G technology was introduced. These effects on renewable share, energy spilled, average LCOE and emissions were found to be greater for adding V2G than for doubling the EV fleet. The study analysed a future island power system with a maximum found renewable share of 30% and charging at work (public charging) was only possible for 5-6% of the vehicles. Results were presented for i.a. 25,000 EVs without V2G, 25,000 EVs with V2G and 50,000 EVs with V2G. The introduction of 25,000 EVs showed a marginal increase in the renewable share compared to the baseline without EVs. Adding V2G capacities to these 25,000 vehicles on the other hand showed a significant increase. Lastly, moving to 50,000 EVs with V2G showed a marginal increase compared to the 25,000 EVs with V2G scenario.

In the sensitivity analysis presented in section 7.4 of this thesis, it was shown that the majority of the benefits could be attributed to the first group of 25,000 EVs, and that the second group of EVs were responsible for a relatively small share. Furthermore, it was found that adding V2G generally allowed for further reductions in curtailed energy, around 1 percentage point for dominant wind and 2 percentage points for dominant solar for various cases. To be able to evaluate the statement made in [60], the amounts of curtailed energy found for public&home charging in the dominant solar scenario, are summarised in table 8.1.

Table 8.1 Overview of curtailed energy shares (as percentage of system energy) and percentage point reductions compared to the base case, for different cases of number of EVs and V2G capabilities found in this thesis.

Case	Curtailed energy	Reduction	Description
No EVs	24%	- - -	base case
25,000 EVs – G4V	17%	-7%p	
25,000 EVs – G4V	14%	-3%p.	reference case in sensitivity analysis
50,000 EVs – V2G	12%	-2%p.	

These results are in contrast to the conclusions of [60], as it was found that the introduction of 25,000 vehicles allowed for the largest reduction in curtailed energy (-7%p.), followed by doubling the EV fleet (-3%p.), and ultimately by adding V2G capabilities (-2%p.). Based on these results, it may be said that the conclusion that V2G utilisation impacts the benefits considerably more than doubling the EV fleet, does no longer stand. The difference may be attributed to the fact that in [60], no degradation costs or driving constraints were imposed on the vehicles. Thus making V2G utilisation in their analysis more attractive and more impactful.

Furthermore, the authors found an emission reduction of 125 kton CO_2 emissions per year for 50,000 EVs. This thesis showed a reduction of 230 kton CO_2-eq emissions per year, i.e. 84% more. The difference can be explained through the relatively high emission values assumed for Aruba and the fact that in this thesis total equivalent GHG emissions were considered, instead of solely CO_2 emissions (the difference between these is around 75% based on data shown in table 5.14 in section 5.8).

Pina et al. [98] found that controlled charging (without V2G) doubled the share of renewable energy used to charge EVs, i.e. an increase in the share of 100%. In the results presented in this thesis, this share depends strongly on the dominant renewable source scenario and the implementation of public charging infrastructure. This effect on the share of EV demand from curtailed energy is summarised in table 8.2.

Table 8.2 Overview of increases in share of EV demand from curtailed energy for different scenarios and cases through the addition of controlled charging found in this thesis.

Factor	**Dominant wind**	**Dominant solar**
Only home	32% to 56% (an increase of 75%)	16% to 43% (an increase of 169%)
Public & home	46% to 59% (an increase of 28%)	59% to 86% (an increase of 45%)

Based on the results presented in table 8.2, it can be said that the general conclusion presented in [98] may be overestimated and the share of EV demand from curtailed energy is very dependent on the implemented dominant renewable energy scenario and implementation of public charging stations. For three out of four cases, lower values were found than the doubling indicated in [98]. Only for dominant solar with only home charging, it was found that the share more than doubled through the addition of control, with an increase of 169%.

In [35] it was shown that a 20% penetration of EVs in the total fleet of 55,000 personal vehicles on São Miguel island were able to completely flatten the daily electricity demand profile through controlled charging and V2G utilisation. This contrasts the results presented in this thesis, in which an electric vehicle fleet of 50,000 vehicles was able to considerably reduce residual demand variations, but not completely flatten its profile, due to cost and driving constraints, as discussed on page 92.

Ilic et al. [102] showed that the value of investment in new renewable energy capacity is strongly dependent on the implementation of controlled charging. Moreover, it was found that for a moderate wind and solar scenario with 100% EVs, spilled energy was reduced from 23% to 8% through the addition of control and V2G. Similar results have been found in this thesis. Curtailed energy was reduced from 22% to 12% by adding controlled charging with V2G for the dominant solar scenario. However, this required the inclusion of public charging infrastructure, because for only home charging this value was 17%. This showed the strong dependency on public charging infrastructure to obtain these reductions in curtailed energy.

8.2 Reflection

In this section, choices and assumptions made in the modelling will be reflected on, and their influence on the results will be dicussed.

General

The modelling and simulations assume the implementation of a high penetration of wind and solar energy, a full transition towards electric mobility and the implementation of gas as main fuel source used by WEB Aruba. If this will actually be implemented as such remains unclear.

The model is deterministic, so no uncertainty is taken into account. A probablistic study is needed to reveal the effects of uncertainty in both supply and demand. This entails most notably the production from renewable sources and the demand from EVs.

The Aruban electricity demand is expected to retain its current value in this analysis. Any improvement in e.g. the electricity demand from cooling can drastically decrease this demand and change its profile. This would change the numerical outcomes, but would not subvert the general characteristics related to controlled EV charging.

The simulations in this thesis are limited to the month July. However, it was tested that when the same analysis is performed for a whole year, the numerical outcomes change slightly, but the main findings still stand.

In this study a high penetration of intermittent renewables is analysed (70%). For systems with smaller penetrations, the amount of curtailed energy will be smaller, but it is estimated that the role of EVs will be similar. By shifting EV demand, power generation cost reductions can be achieved by avoiding charging at times of peak demand, and instead letting vehicles charge when there is little demand. Thus, enabling greater use of the cheapest forms of generation and reduced use of the most expensive peak power units.

Power generation and dispatch

Since the model is run in one hour time steps, short term intermittency and imbalances are excluded from the model. This would results in a more variable generation profile of conventional sources to cover sudden drops in renewable power generation and frequency stabilisation measures. This last function could be performed by system-scale batteries on a longer time scale and by flywheels on a shorter time scale, but at significant cost. However, not directly dealt with in this thesis, EVs are also able to supply these services.

The implemented unit dispatch attempts to represent the current operation of the power system on Aruba and the resultant outputs consistent with the real-life conditions of the island. The load factors used to ensure this are a pragmatic approach, but a model incorporating automatic generation control would be a more realistic approximation of the future situation. The same goes for the constant spinning reserve requirement. In the future, this reserve constraint will be implemented differently, although it may still reflect for example the sudden loss of power from a 30 MW wind farm.

In the model the steam units are assumed to provide base load power and set the grid frequency. In the future, the individual (not-modelled) gas turbine or even the reciprocating engines may also be used to perform this function. Because these units are needed to retain grid frequency and their power cannot easily be curtailed, renewable power will need to be curtailed. However, in a realistic setting, there are constraint as to how much power may be curtailed, as is stipulated in the contract. This may affect the power dispatch as is assumed in the model and could therefore result in the need for less generation from conventional sources or even the need to switch off a unit. This could possibly result in a destabilising effect on the grid.

Grid capacity and congestion issues are neglected in this thesis. These influences will presumably decrease the positive outcomes in this thesis, as not all power will in reality be able to flow as is assumed.

Renewable generation

The model implements a simplistic approach to represent generation from renewables wind and solar. It is able to provide general insight on long-term system level, but does not provide detailed insights per day or per hour. An example is the fact that no specific inclination of solar panels is assumed here. In a real-life situation this would affect the per hour power output, however, its weekly production would be approximately the same as calculated by the model. In the case of wind power an important factor is the assumed linear relation between average wind speed and average power output. This assumption underestimates the production from wind energy, because the energy content of wind energy varies with the cube (the third power) of wind speed. Sub-hourly wind speeds above average would result in a higher hourly power output than is assumed here. This may result in the difference in share of wind power between data from WEB Aruba and model output as discussed in section 5.4.

Moreover, the conversion of measured wind speeds to hub height make use of log wind profile law. Albeit that this is a commonly used method to estimate wind power production figures, it relies on certain assumptions such as stable atmospheric conditions and an approximate value for surface roughness length. This thus provides an estimation of wind power production, but may result in more variance in wind power production.

Renewable resource

Input data of demand, temperature and wind speed were taken for the year 2015. Measured wind speed and temperature data were taken from the Integrated Surface Database (ISD) of the National Oceanic and Atmospheric Administration. Demand data was obtained from WEB Aruba. Unfortunately, the weather station present did not also measure solar irradiance, and therefore this data was sourced elsewhere, i.e. from the Meteonorm database. It makes use of data over a 10 year period to construct irradiance data for a 'typical year.' Consequently, using these two different data sources has the implication that any physical correlation between the wind speeds, temperature and solar irradiance is not be kept intact. This fact could influence the system operation most notably the ratio between production from solar and wind. However since it is only the irradiance data that was synthesised, which follows a much more predictable pattern than that of the wind speeds, it is likely that the distortion to this correlation, and the consequent impact of this, is quite minimal.

Due to its excellent and very constant wind and solar resources, capacity factors for both technologies are high on Aruba. In [141] it was found that Aruba only has 350 hours per year of zero production from wind and solar. For other islands, this study found significantly higher values, i.a. 1650 hours for Rhodes, 1260 hours for Streymoy and 2220 hours for Sumba. For these other islands it proved to be much more costly to reach high penetration levels of wind and solar, since much more capacity needs to be installed. As a result, peaks and valleys of residual demand will be larger. This implies that the moments when energy is curtailed, and EV charging is stimulated, will be scarcer compared to Aruba where this was found to occur almost daily. On these other islands, the EVs will need to be able to postpone charging longer and some may not be able to, because of driving constraints. Athough scarcer, these amounts of energy curtailed during periods of overproduction will be larger, and may prove to be too large for EVs to absorb. These notions would lead to more generation from conventional fossil-fuel generators and smaller reductions of curtailed energy through controlled charging. The presented results for Aruba are believed to reflect the general characteristics of a future island power system with controlled charging of a large fleet of EVs well, but due to its unique resources, the results will be more favourable compared to other islands.

Electric vehicles

For lack of sufficient data, Dutch mobility data was used to model drive patterns (a similar approach was followed in Pina et al. [98] where Portugues mobility data was used for the case of Flores island). Although scaled and fitted to the case of Aruba, this will still affect the outcomes presented here, but will not subvert the main conclusions.

EV battery capacity and efficiency values reflect the total (cumulative) system characteristics rather well, however do not provide much detail on EV user level. An example is the assumption that EV efficiency is constant throughout the simulation days. Similarly to the situation of power generation and dispatch, this would affect the hourly outcomes of the model, but will not significantly impact the general insights shown in this thesis.

Storage

In [141] it was shown that for the case of Aruba with a 70% penetration of wind and solar energy, it is more attractive to curtail energy than to implement large-scale battery or pumped hydro storage (PHS) solutions, due to their high cost. Only for higher penetrations of 90%, it was found that PHS was installed, and both its capacity and usage were very small compared to the other islands within the scope of the analysis. This contrasts the results found in this thesis, as it was found that V2G storage in the electric vehicles' batteries did prove to be economically attractive, already at the 70% penetration. Consequently, because V2G storage costs are lower than those of PHS and significantly lower than large-scale battery storage, V2G storage would be the preferred and only form of storage needed to achieve Aruba's goal of 100% renewable electricity. It is thus recommended that a study is performed that includes V2G storage in the analysis of the six islands reviewed in [141].

In general, if and how much storage is implemented in a system is highly dependent on its costs. In this thesis, the battery degradation costs and the added cost of including V2G capabilities into the charging infrastructure were assumed to be the only costs of storage by electric vehicles. The assumed degradation costs were retrieved from an experimental study [185] that estimated the Li-ion battery degradation costs as a result of vehicle-to-grid utilisation. There are many uncertainties regarding real-life costs, and these will depend on the depth-of-discharge, use conditions, type and capacity of EV battery, etc. The influence of a 50% lower and a 50% higher degradation cost was tested in the sensitivity analysis in section 7.4, and was found to not signifcantly change the general findings of this thesis. However, these costs remain considerably lower than those of other forms of storage.

Optimisation

Although minimizing charging costs with the aims that are discussed in section 5.5., it does not necessarily mean that CO_2 emissions are minimised. This is because dispatchable gas-based generation is always able to follow demand, and the effect on emissions of these ramping, start-up and shut down events is not taken into account. In other words, a linear relation is assumed between produced power and emissions. In reality this is not the case. If the change in efficiency of these generators with respect to their nominal operating point would be considered, there will be another optimum where fuel consumption and thus CO_2 emissions are minimised. The same holds true for the costs of generation. These depend on several other factors such as the costs for ramping and starting up and shutting down, as these events influence the wear and tear of each machine.

The dynamic electricity price is modelled as an exponential curve. This implies that it only takes on positive values. An alternative price formulation could also lead to negative prices, reflecting a situation where consumers would be paid to consume electricity. Such a price signal is believed to not change the outcomes of the G4V cases significantly, since the basic incentives of demand response would not change, i.e. charging would still be discouraged at times of high prices and charging would be encouraged at times of low or negative price values.

For the V2G cases on the other hand, under the assumption that the positive side of the curve would be kept the same, this would lead to an increase in utilisation of storage in electric vehicles, since the price margin between high prices and low prices would become greater. Thus allowing more energy to be shifted. To explain, in the performed simulations, there is a limit to the amount of energy for which it is economically attractive to be shifted, because after each vehicle's charge action, the price is recalculated. This implies that not only the power profile is flattened, but also the price profile. For a more detailed explanation, see page 91-92. Negative prices make it attractive for more energy to be shifted, and will therefore result in more V2G action.

Economic analysis

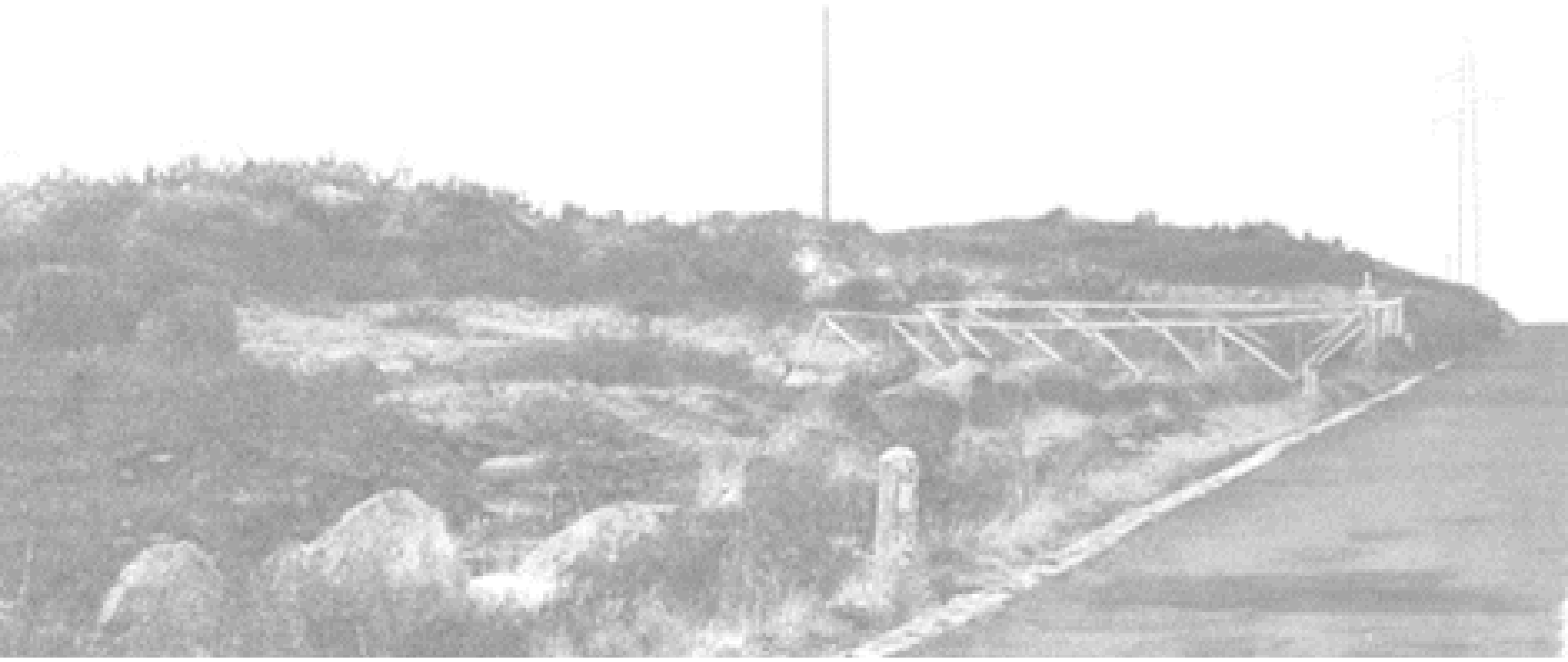
Although commonly used, and widely accepted, the method of levelised cost implemented here is a simplistic way to model power system cost and include charging infrastructure.

Cost assumptions are rough future estimates and will be very dependent on market developments and the specific considerations for each island, i.e. how dependent the island will be to hire foreign experts or companies and at what cost.

Grid reinforcement costs are not taken into account because there is no data available that deal with this type of grid investments. These will greatly influence the cost of EV integration and thus the system levelised cost. For public charging, this will be very dependent on the way EV charging stations are implemented and how these are connected to rooftop solar power systems. If solar power can be used directly on-site to charge vehicles, the problems of grid integration of both can be avoided. If the distribution grid is needed to transfer this power, major grid reinforcements will presumably be needed. For the only home charging cases this effect will not be as large, since the power level used here is lower and the grid is overdimensioned to be able to accommodate airconditioning peak loads.

As a result of the assumption that the transition to gas-fueled dispatchable generation will be implemented in the near future, any costs related to refitting these turbines and engines are not taken into account.

In this thesis, no cost of carbon is taken into account. There are indications that this may change in the future. This will make the business case for renewables and electric mobility more attractive.



9. CONCLUSION

9. CONCLUSION

This thesis has investigated both the technical performance as well as the economic pontential of the implementation of controlled and vehicle-to-grid charging, and the addition of public and high power charging infrastructure, for large-scale electric-vehicle charging within a future island power system where solar and wind power together produce 70% of electricity demand. A case-study was performed for the island Aruba.

9.1 Conclusions

Technical performance

EVs were found to have a large degree of flexibility and thus very well able to shift their demand to times when this is beneficial within an island power system with a large penetration of renewables. In doing so, renewable energy utilisation was shown to be greatly increased due to controlled EV charging and the addition of public charging infrastructure.

These technical benefits were very dependent on the implemented control strategy and public charging infrastructure. Furthermore, the role of controlled EV charging and public charging infrastructure was highly dependent on the chosen transition scenario.

The residual power demand profile was shown to be flattened significantly by avoiding to induce EV demand at peak hours, but instead matching power production from renewable sources. This way, EVs were able to reduce curtailed energy up to a point where the majority of EV demand originated from otherwise curtailed power, thus causing almost no increase of dispatchable conventional generation. Together, the addition of controlled charging and public charging stations roughly halved the amount of curtailed energy compared to the situation with no EVs. No significant decrease was visible through the move to a high power infrastructure, indicating that for the modelled EVs a low power infrastructure did not form a constraint in their ability to take up curtailed power.

When vehicle-to-grid (V2G) capabilities were implemented, all energy required for the EVs originated from curtailed energy for dominant solar. In these cases, significant peak shaving was performed by EVs. Although, despite 50,000 vehicles being electric and capable of performing V2G functions, EVs alone were found not to completely flatten the residual demand profile by acting as storage, due to cost constraints.

Consequently, greenhouse gas emissions of power generation were shown to increase only marginally, compared to the base case without EVs for dominant solar. Contrastingly, uncontrolled only home charging showed significant increases in emissions, for both dominant renewable energy source scenarios.

Economic potential

The combined move to renewable power and controlled EV charging was shown to decrease energy unit costs for both scenarios. This led to both reductions in power generation cost and vehicle running cost. Investment in control was shown to be always attractive, though for public charging infrastructure this depends on the scenario.

The results implied that if social and cultural conditions are right, and the island would be able to implement a dominant wind strategy, which would lead to a lower system levelised cost of electricity than dominant solar, there is no economic incentive for the addition of public charging stations, i.e. the power generation cost reductions were found not to outweigh charging infrastructure cost. Both controlled G4V and V2G charging on the other hand, did show a lower system levelised system cost.

Conversely, when a dominant solar scenario was implemented, the addition of public charging stations was shown to lead to a lower system levelised system cost. Thus indicating that it makes sense to install these levels of public charging infrastructure.

9.2 Recommendations

General recommendations

This study has estimated the combined technical performance and economic potential for smart integration of electric vehicles into an island power system. Naturally, there are follow-up studies required to better estimate and validate this potential, taking into account detailed considerations and small-scale effects that have been ignored in this thesis. This would endorse the possible benefits for the case of Aruba, as well as for the general case of islands. Therefore, possible follow-up research opportunities are discussed here:

- From a technical point of view, possible follow-ups include the analysis of large-scale EV integration on the sub-hourly operation and stability of the power system, because one of the majors shortcomings of this study is that it has not addressed the operation of the electricity supply system on a minute and second scale. Modelling the power system in more detail, with smaller time steps and by including the required electrical components and grid infrastructure would provide more certainty on the feasibility of these discussed cases in reality, and give a clearer picture on the potential infrastructure reinforcements and generation reserves required.

- A model incorporating automatic generation control, which is planned to be implemented on Aruba in 2017, and unit commitment optimisation constitutes a natural follow-up from the dispatch approach implemented in this thesis, although more accurate cost data would be required to put this to full use. Other than just minimising cost, future research can give insight into the effects of performing a multi-objective optimisation where costs of charging, costs of dispatchable generation and CO_2 emissions are minimised.

- Future research can be combined with planned research projects in the Smart Community on Aruba. Here for example local peak shifting through controlled charging and peak shaving through V2G could be tested, both from a technical and a social perspective, and to see its impact on low-voltage networks. It would also provide a useful testing area for the use of EVs to provide other ancillary services such as spinning reserve and voltage support. Furthermore, V2G can be applied in multiple ways, such as a more top-down large-scale based on the renewable availability and thus system electricity price, or bottom-up small-scale based on the renewable availability versus electrical load in building or home.

- It will be very interesting to further investigate the complementarity between combined solar power production and EV charging. This can prove to have substantial benefits from both a technical and economical perspective, by reducing grid integration issues and improving the overall business case of public charging.

- And generally, from a socio-technical point of view, it is needed to analyse these future scenarios and develop roadmaps towards them from a societal and policy perspective. This relates to the development, implementation and evaluation of strategies and processes in striving towards the system configurations discussed in this thesis.

On the following page, recommendations are given for the case of Aruba that deal with the challenges and opportunies related to the implementation of smart EV integration.

Implementation challenges and opportunities for Aruba

Government action is crucial is this transition to electric mobility. The Aruban government currently sees the market as being the issue for electric vehicles. To give some context, people on Aruba mostly buy a vehicle on a personal loan [136]. Therefore, one of the focus points would be to look at working together with the banking institutions to set up green loans that can be used to invest in clean technologies. And more importantly, the Aruban government has not yet set a goal for sustainable transport. It is recommended that *there should be a sustainable transportation goal aside from Aruba's current goal of moving to 100% sustainable energy in 2020.*

Furthermore, to allow for a swift uptake of electric vehicle use, several external and boundary conditions for this development need to be met. Think of facilities such as emergency response units that know how to deal with an electric vehicle, and more importantly its battery, in the case of an emergency. Also car dealers need to adapt to be able to service these vehicles regularly. Employees and car mechanics needs to be re-educated for this purpose. Government bodies should lead the charge in formulating policies that deal with these matters.

This thesis has shown the potential for controlled EV charging and V2G storage, however the implementation of e.g. the investigated charge control has not been dealt with in this thesis. It is recommended for Aruba to analyse and dive deeper into, for example, investment strategies and grid reinforcement costs of EV charging infrastructure, in order to determine and substantiate implementation strategies for the investigated scenarios.

It will for example be of interest to look into strategies of creating a communication platform to couple the EVs to the power system. Creating this type of ICT infrastructure and determining what standards will be used for connections, protocols, etc. will be a challenge. The same goes for building and maintaining the system with local knowledge and expertise. An alternative to the price signal discussed in this thesis is a grid signal to indicate to or alert charging equipment when charging is optimal. This can be a relatively low-tech implementation such as done currently in the Netherlands where the non-smart energy meter receives a frequency pulse signal to switch from day- to night-time tariff and vice-versa. Another option would be by means of changes in the grid's frequency. A deviation from the standard (60 Hz for Aruba), is then used to stimulate or discourage charging.

This study has shown that from a system perspective, there is no need for a high power infrastructure. However, it will be of interest to look into the role of DC fast charging infrastructure (≥ 50 kW), which although it is not necessary to meet Aruba's demands, may prove to be the preferred global method of public EV charging.

Flywheels and underwater compressed air storage systems are currently under development on Aruba. It will be interesting for the island's energy policy to investigate the complementarity between V2G storage and these forms of short- and long-term storage. Moreover,, to test possible structures and strategies, the Smart Community or public transport could be used as pilot for large-scale EV smart charging implementation. This will be of great importance to the utilities which - if storage through V2G is implemented - want to have control over these distributed storage units. Thus ensuring system reliability, i.e. limiting the stochastic influences, as it is their responsibility for the entire Aruban population and the tourists residing on the island.

10. APPENDICES

10. APPENDICES

Appendix 1 - Solar radiation data Aruba

These data have been used in the model to calculate the power output from solar energy. The table gives an oveview of the global and diffuse horizontal radiation. This data is then presented as a stacked bar graph in the first figure to allow for a quick visual comparison of different months. Furthermore, the second figure presents the variations in daily global horizontal radiation. Both figures show a very constant influx of solar energy on Aruba, without much seasonal influence.

Table A1.1 Solar radiation data, downloaded from [137] for the island of Aruba.

Month	H_Gh	H_Dh	H_Bn	Ta
	[kWh/m2]	[kWh/m2]	[kWh/m2]	[°C]
January	149	61	137	26,9
February	145	61	122	27,1
March	176	80	135	27,7
April	168	87	110	28,4
May	171	85	116	29,0
June	160	83	105	29,1
July	168	86	116	29,1
August	177	83	127	29,5
September	166	80	118	29,6
October	146	73	106	29,1
November	133	61	116	28,4
December	131	60	122	27,5
Year	1891	900	1431	28,5

H_Gh: Irradiation of global radiation horizontal
H_Dh: Irradiation of diffuse radiation horizontal
H_Bn: Irradiation of beam
Ta: Air temperature

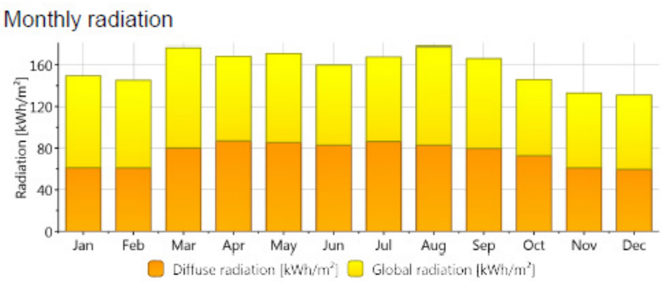


Figure A.1.1 Monthly radiation, downloaded from [137] for the island of Aruba.

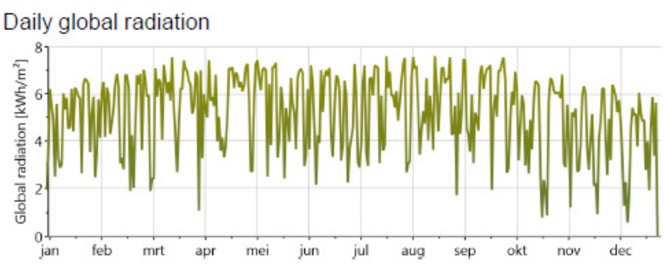


Figure A.1.2 Monthly radiation, downloaded from [137] for the island of Aruba.

Appendix 2a - Driving characteristics on Aruba

These data - presented in figure A2.1 - show for different regions on Aruba what the distance from home to work is [186]. This can be compared to the Dutch data presented in figure A2.2 where the amount of drivers is compared to their daily distance driven. However, here *Arrival time* is presented as an extra factor. From these it can be seen that the overall correlation is the same and that the large majority lives very close to work and that there is an non-linear trend towards longer distances driven. Note that in the case of the Netherlands there is a second peak for long distances since here long-distance (read international) trips are included.

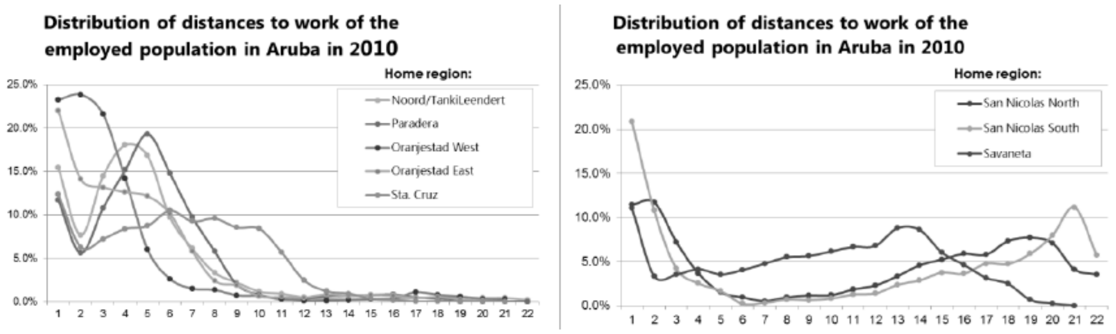


Figure A2.1 Distribution of distances from home to work, from [186] for the island of Aruba.

Appendix 2b - Driving characteristics in the Netherlands

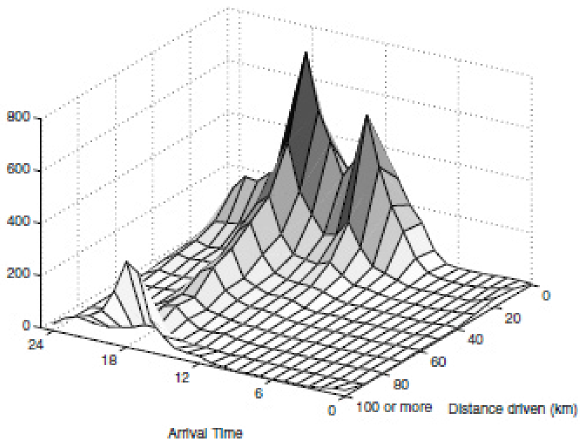


Figure A2.2 Distribution of distances from home to work, from [49] for the Netherlands.

Appendix 3 - Battery behaviour characteristics

These graphs presented in figure A3.1 show the Peukert effect, i.e. a decrease in battery capacity for larger discharge currents. It can be seen that for c-rates in the range of 0.1 to 1.0, there is a negligible drop in capacity.

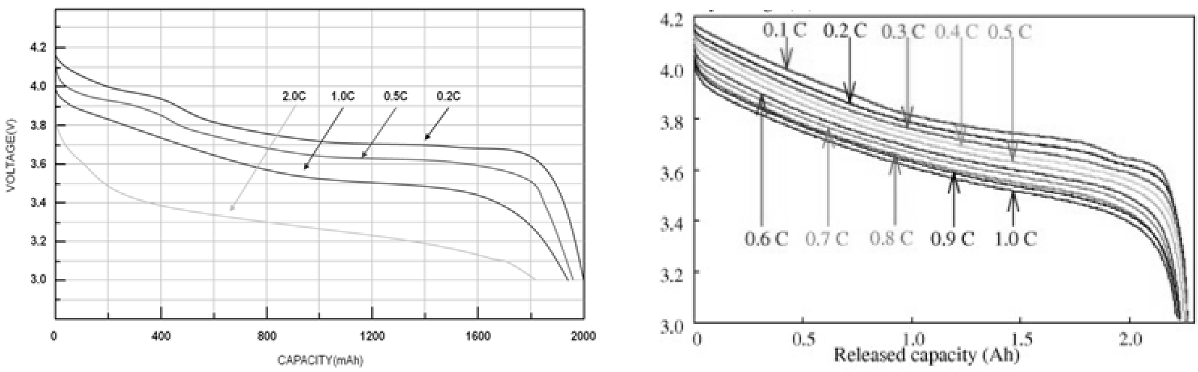
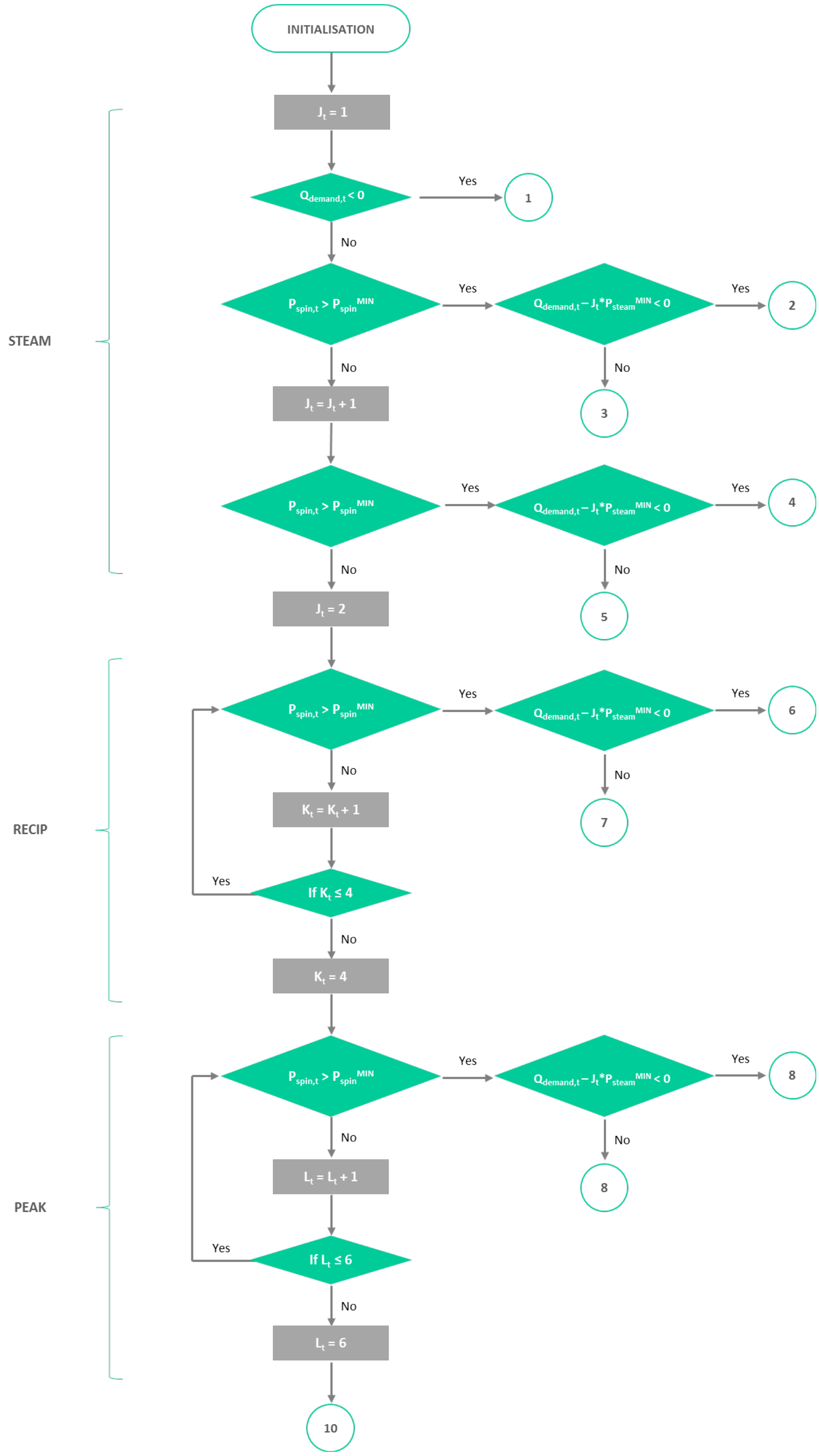


Figure A2.2 Distribution of distances from home to work, from [49] for the Netherlands.

Appendix 4a - Power dispatch flow chart

The dispatch strategy implemented in the model is shown here, which is based on retaining sufficient spinning reserves at all times. Generator units are dispatched in a specific order, based on cost and inertia. Their power output is determined by the equations presented in appendix 4b. Each encircled number refers to a set of equations.



Appendix 4b - Power dispatch equations

These equations, linked to the flow chart in appendix 4a, explain the dispatch strategy implemented in the model in more detail, and determine the specific power output of each generator unit. This is based on the number and type of units online, residual demand and the load factor defined on page 56.

1

$$
\begin{aligned}
&P_{steam,1,t} = P_{steam,j}^{min} \\
&P_{steam,2,t} = 0 \\
&P_{recip,k,t} = 0 \quad \forall k \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = Q_{demand,t} - P_{steam,t}
\end{aligned}
$$

2

$$
\begin{aligned}
&P_{steam,1,t} = P_{steam,j}^{min} \\
&P_{steam,2,t} = 0 \\
&P_{recip,k,t} = 0 \quad \forall k \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = Q_{demand,t} - P_{steam,j}^{min}
\end{aligned}
$$

3

$$
\begin{aligned}
&P_{steam,1,t} = Q_{demand,t} \\
&P_{steam,2,t} = 0 \\
&P_{recip,k,t} = 0 \quad \forall k \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = 0
\end{aligned}
$$

4

$$
\begin{aligned}
&P_{steam,1,t} = P_{steam,j}^{min} \\
&P_{steam,2,t} = P_{steam,j}^{min} \\
&P_{recip,k,t} = 0 \quad \forall k \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = Q_{demand,t} - J_t * P_{steam,j}^{min}
\end{aligned}
$$

5

$$
\begin{aligned}
&P_{steam,1,t} = Q_{demand,t} - P_{steam,j}^{min} \\
&P_{steam,2,t} = P_{steam,j}^{min} \\
&P_{recip,k,t} = 0 \quad \forall k \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = 0
\end{aligned}
$$

6

$$
\begin{aligned}
&P_{steam,1,t} = Q_{demand,t} - P_{steam,2,t} - P_{recip,k,t} \\
&P_{steam,2,t} = P_{steam,j}^{min} + {}^{2}/_{3}\, f_{load}\,(P_{steam,j}^{max} - P_{steam,j}^{min}) \\
&P_{recip,k,t} = P_{recip,k}^{min} \qquad for\ k = 1, \dots, K_t \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = 0
\end{aligned}
$$

7

$$
\begin{aligned}
&P_{steam,1,t} = Q_{demand,t} - P_{steam,2,t} - P_{recip,t} \\
&P_{steam,2,t} = P_{steam,j}^{min} + {}^{2}/_{3}\, f_{load}\,(P_{steam,j}^{max} - P_{steam,j}^{min}) \\
&P_{recip,k,t} = {}^{3}/_{2}\, f_{load}\, P_{recip,k}^{max} \qquad for\ k = 1, \dots, K_t \\
&P_{peak,l,t} = 0 \quad \forall l \\
&P_{curtail,t} = 0
\end{aligned}
$$

8

$$
\begin{aligned}
&P_{steam,1,t} = P_{steam,j}^{min} \\
&P_{steam,2,t} = P_{steam,j}^{min} \\
&P_{recip,k,t} = P_{recip,k}^{min} \quad \forall k \\
&P_{peak,l,t} = P_{peak,l}^{min} \qquad for\ l = 1, \dots, L_t \\
&P_{curtail,t} = Q_{demand,t} - J_t * P_{steam,j}^{min}
\end{aligned}
$$

9

$$
\begin{aligned}
&P_{steam,1,t} = Q_{demand,t} - P_{steam,2,t} - P_{recip,t} - P_{peak,t} \\
&P_{steam,2,t} = P_{steam,j}^{min} + {}^{2}/_{3}\, f_{load}\,(P_{steam,j}^{max} - P_{steam,j}^{min}) \\
&P_{recip,k,t} = {}^{3}/_{2}\, f_{load}\, P_{recip,k}^{max} \quad \forall k \\
&P_{peak,l,t} = {}^{3}/_{2}\, f_{load}\, P_{peak,l}^{max} \qquad for\ l = 1, \dots, L_t \\
&P_{curtail,t} = 0
\end{aligned}
$$

10

$$
\begin{aligned}
&P_{steam,1,t} = (Q_{demand,t} - P_{recip}^{max} - P_{peak}^{max})/J_t \\
&P_{steam,2,t} = P_{steam,j}^{max} \\
&P_{recip,k,t} = P_{recip,k}^{max} \quad \forall k \\
&P_{peak,l,t} = P_{peak,l}^{max} \quad \forall l \\
&P_{curtail,t} = 0
\end{aligned}
$$

BIBLIOGRAPHY

[1] UNFCC Newsroom (2015). Retrieved from: http://newsroom.unfccc.int/unfccc-newsroom/finale-cop21/

[2] European Commission (2016). Retrieved from: https://ec.europa.eu/clima/policies/transport/vehicles/cars/index_en.htm

[3] Climate Action Tracker (2015). Retrieved from: http://climateactiontracker.org/countries/

[4] BP (2015). BP Statistical Review of World Energy June 2015, 64th edition.

[5] Center for Climate and Energy Solutions (2015). Retrieved from: http://www.c2es.org/docUploads/china-factsheet-formatted-10-2015.pdf

[6] The White House (2016). Retrieved from: https://www.whitehouse.gov/climate-change

[7] Organisation for Economic Co-operation and Development (2015). Retrieved from: http://www.oecd.org/env/cc/Overview-of-INDCs-Sep2015.pdf

[8] UNFCC (2015). Retrieved from: http://www4.unfccc.int/submissions/INDC/Published%20Documents/Indonesia/1/INDC_REPUBLIC%20OF%20INDONESIA.pdf

[9] Rijksoverheid (2016). Retrieved from: https://www.government.nl/topics/climate-change/contents/national-measures

[10] Lazard (2015). *Lazard's Levelized Cost Of Energy Analysis—Version 9.0*. Retrieved from: https://www.lazard.com/media/2390/lazards-levelized-cost-of-energy-analysis-90.pdf

[11] Cleantechnica (2015). Retrieved from: http://cleantechnica.com/2015/07/21/worlds-cheapest-solar-power-project-dubai-achieves-financial-closure/

[12] US Energy Information Administration (2016). *Annual Energy Outlook 2016*. August 2016.

[13] Abd-el-Motaleb, A. and Hamilton, D. (2015). *Modelling and sensitivity analysis of isolated microgrids.* Renewable and Sustainable Energy Reviews 47, pp. 416–426.

[14] Ally, C., Bahadoorsingh, S., Singh, A. and Sharma, C. (2015). *A review and technical assessment integrating wind energy into an island power system.* Renewable and Sustainable Energy Reviews 51, pp. 863–874.

[15] Energinet (2016). Retrieved from: http://energinet.dk/EN/El/Nyheder/Sider/Dansk-vindstroem-slaar-igen-rekord-42-procent.aspx

[16] Albadi, M. and El-Saadany E. (2010). *Overview of wind power intermittency impacts on power systems.* Electric Power Systems Research 80, pp. 627–632.

[17] Georgilakis, P. (2006). *Technical challenges associated with the integration of wind power into power systems.* Renewable and Sustainable Energy Reviews 12, pp. 852–863.

[18] Holttinen, H. Meibom, P, Orths, A. et al. (2011). *Impacts of large amounts of wind power on design and operation of power systems, results of IEA collaboration.* Wind Energy 14, pp. 179–192.

[19] Lund, H. and Münster, E. (2006). *Integrated energy systems and local energy markets.* Energy Policy, Vol. 34, pp. 1152-1160.

[20] Intergovernmental Panel on Climate Change (2014). *Climate Change 2014 - Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[21] International Energy Agency (2011). T*echnology Roadmap Electric and plug-in hybrid electric vehicles.*

[22] Jorgensen, P. (2007). *Samsø, a Renewable Energy Island. 10 years of Development and Evaluation.*

[23] Pacific Institute for Climate Solutions (2015). *Norway's electric vehicle revolution: Lessons for British Columbia*. Briefing note 2015 – 43. 26 October 2015.

[24] Ministry of Transport, Public Works and Water Management 2011. *Elektrisch Rijden in de versnelling, Plan van Aanpak 2011-2015.*

[25] Ministery of Economic Affairs (2016). *Energierapport Transitie naar duurzaam.*

[26] Porsche (2016). Retrieved from:
http://press.porsche.com/news/release.php?id=842

[27] Steinbuch, M. (2015). Retrieved from:
https://steinbuch.wordpress.com/2015/03/04/2018-the-take-off-for-electric-driving/

[28] Croes, G.(2015). *The shift to electric cars at WEB Aruba NV.*

[29] InsideEVs (2016). Retrieved from:
http://insideevs.com/most-electric-vehicle-owners-charge-at-home-in-other-news-the-sky-is-blue/

[30] Pluginsights (2016). http://www.pluginsights.com/services/

[31] PEV Collaborative (2016). Retrieved from:
http://www.pevcollaborative.org/sites/all/themes/pev/files/4_april_PEV_cumulative.pdf

[32] California Independent System Operator (2016). Retrieved from:
https://www.caiso.com/Documents/FlexibleResourcesHelpRenewables_FastFacts.pdf

[33] Nelder C., Newcomb, J. and Fitzgerald, G. (2016). *Electric Vehicles as distributed energy resources.* Rocky Mountain Institute 2016.

[34] Jorgensen, K. (2008). *Technologies for electric, hybrid and hydrogen vehicles: electricity from renewable energy sources in transport.* Utilities Policy 16, pp. 72-79.

[35] Kadurek, P., Ioakimidis, C., and Ferrão, P. (2009). *Electric Vehicles and their Impact to the Electric Grid in isolated systems.* Power Engineering 2009

[36] Kempton, W. and Letendre, S. (1997). *Electric Vehicles as a New Power Source for Electric Utilities.* Transp. Res. Part D, Vol 2, No. 3, pp. 157-175.

[37] Kempton, W. and Tomic, J. (2005). *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy.* Journal of Power Sources, Vol. 144, No.1, pp. 280–294.

[38] Kempton, W. (2007). *System and method for assessing vehicle to grid (V2G) Integration.* United States Patent Application: 0070282495.

[39] Yue, C., Chen, C., and Lee, Y. (2016). *Integration of optimal combinations of renewable energy sources into the energy supply of Wang-An Island.* Renewable Energy, Vol. 86, pp. 930-942.

[40] Lund, H. (2003). *Excess electricity diagrams and the integration of renewable energy.* International Journal of Sustainable Energy, 23:4, pp. 149-156.

[41] Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R. (2007). *Functions of innovation systems: A new a pproach for analyzing technological change.* Technological Forecasting & Social Change 74, pp. 413–432

[42] Geels, F. (2002). *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case study.* Research Policy 31, pp. 1257–1274.

[43] Duurzaam Bedrijfsleven (2012). Retrieved from:
http://www.duurzaambedrijfsleven.nl/energie/280/verduurzaming-caribisch-nederland-krijgt-vorm

[44] Energie Overheid (2011). Retrieved from:
http://www.energieoverheid.nl/2011/10/25/tno-opent-living-lab-voor-duurzame-energie-op-aruba/

[45] Europa Nu (2012). Retrieved from:
http://www.europa-u.nl/id/vj1846ovits4/nieuws/wnf_in_2050_kan_aruba_alle_enodigde?ctx=vgaxlcr0e003

[46] PIOJ (2012). *Statement at Worldwatch Institute Sustainable Energy Roadmap Stakeholder Consultation*. 27 November 2012.

[47] Rious, V., and Perez, Y. *Review of supporting scheme for island power system storage.* Renewable and Sustainable Energy Reviews 29, pp. 754-765.

[48] Blok, K. (2006). *Introduction to Energy Analysis.* April 2007. Amsterdam: Techne Press.

[49] Verzijlbergh, R. (2013). *The Power of Electric Vehicles Exploring the value of flexible electricity demand in a multi-actor context.* Delft University of Technology, Dissertation.

[50] Andersen, P. (2015). Retrieved from: http://www.amsterdamvehicle2grid.nl/wp-content/uploads/2015/04/Peter-Bach-Andersen.pdf

[51] Letendre, S. and Kempton, W. (2002). *The V2G Concept: A New For Model Power? Connecting utility infrastructure and automobiles.* Public Utilities Fortnightly, February 15, 2002.

[52] Kempton, W. and Tomic, J. (2004). *Vehicle-to-grid power fundamentals: Calculating capacity and net revenue.* Journal of Power Sources, Vol. 144, No. 1, pp. 268-279.

[53] Gorguinpour, C. (2013). *The DoD V2G Pilot Project Overview.* Office of the Assistant Secretary of the Air Force: Installations, Environment & Logistics. US Department of Defence.

[54] European Parliament (2015). *Energy Storage: Which Market Designs and Regulatory Incentives Are Needed?* Directorate General for Internal Policies-Policy Department A: Economic And Scientific Policy.

[55] Ersal, T., Ahn, C., Hiskens, I., Peng, H. and Stein, J. (2011). *Impact of Controlled Plug-In EVs on Microgrids: A Military Microgrid Example.* Power and Energy Society General Meeting, 2011 IEEE.

[56] Elektrec (2016). Retrieved from: https://electrek.co/2016/05/11/nissan-vehicle-to-grid-enel-uk/

[57] Tesla, 2016. Retrieved from: https://onestepoffthegrid.com.au/tesla-explains-evs-selling-electricity-grid-not-good-sounds

[58] Fitzgerald, G., Mandel, J., Morris, J. and Touati, H. (2015). *The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid.* Rocky Mountain Institute, September 2015.

[59] National Renewable Energy Laboratory (2011). *Operating Reserves and Variable Generation. A comprehensive review of current strategies, studies, and fundamental research on the impact that increased penetration of variable renewable generation has on power system operating reserves.* August 2011

[60] Diaz, A., Ramos-Real, F., Marrero, G. and Perez, Y. (2015). *Impact of Electric Vehicles as Distributed Energy Storage in Isolated Systems: The Case of Tenerife.* Sustainability 2015, Vol. 7, pp. 15152-15178.

[61] Ma H. and Chowdhury, B. (2010). *Working towards frequency regulation with wind plants: combined control approaches.* IET Renewable Power Generation, Vol. 4, No. 4, pp. 308-316.

[62] Erlich, I. (2010). *Primary frequency control by wind turbines.* Proceedings of the IEEE Power and Energy Society General Meeting, Minneapolis, MN, July 2010.

[63] Shafiei, E. et al. (2012). *An agent-based modeling approach to predict the evolution of market share of electric vehicles: A case study from Iceland.* Technological Forecasting & Social Change 79, pp. 1638–1653.

[64] Verzijlbergh, R., Lukszo, Z. and Ilic, M. (2012). *Comparing different EV charging strategies in liberalized power systems.* 9th International Conference on the European Energy Market, pp. 1-8.

[65] Clement-Nyns, K. et al. (2010). *The impact of charging plug-in hybrid electric vehicles on a residential distribution grid.* IEEE Transactions on Power Systems, Vol. 25, No. 1, February 2010.

[66] San Roman, T. et al. (2011). *Regulatory framework and business models for charging plug-in electric vehicles: infrastructure, agents, and commercial relationships.* Energy Policy, Vol.39, No. 10, October 2011, pp. 6360–6375.

[67] Lerch, C., Kley, F., and Dallinger, D. (2011). *New business models for electric cars—A holistic approach.* Energy Policy 39, No. 6, pp. 3392–3403.

[68] Hidrue, M. et al. (2011.).*Willingness to pay for electric vehicles and their attributes.* Resource and Energy Economics, Vol. 33, No. 3, pp. 686-705.

[69] Tamor, M. Gearhart, C. and Angel Soto, C. (2013). *A statistical approach to estimating acceptance of electric vehicles and electrification of personal transportation.* Transportation Research Part C Emerging Technologies, Vol. 26, pp. 125-134

[70] Kuiperi, F. (2015). *Strategy to facilitate EV infrastructure on local level: Using technological changes, preferences of municipalities and the expected demand of EV infrastructure in 2020 on neighbourhood level.* Delft University of Technology, Master Thesis.

[71] Kempton, W. and Tomic, J. (2005). *Vehicle-to-grid power fundamentals: Calculating capacity and net revenue.* Journal of Power Sources, Vol. 144, No. 1, pp. 268-279.

[72] Kempton, W. and Tomic, J. (2005). *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy.* Journal of Power Sources, Vol. 144, No. 1, pp. 280–294.

[73] Lund, H. and Kempton, W. (2008). *Integration of renewable energy into the transport and electricity sectors.* Energy Policy, Vol. 36, pp. 3578-3587.

[74] Budischak, C. et al. (2013). *Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time.* Journal of Power Sources. Vol. 225, pp. 60–74.

[75] Ulleberg, Ø., Nakken, T. and Eté, A. (2010). *The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools.* International journal of hydrogen energy, Vol. 35, No. 5, pp. 1841-1852.

[76] Pina, A., Silva, C. and Ferrão, P. (2012). *The impact of demand side management strategies in the penetration off renewable electricity.* Journal of Energy, Vol. 41, No. 1, pp. 128-13.

[77] De Vries, L. and Verzijlbergh, R. (2015). *Organizing flexibility: how to adapt market design to the growing demand for flexibility.* 12th International Conference on the European Energy Market (EEM).

[78] Verzijlbergh, R., Lukszo, Z. and De Vries, L. (2014). *Renewable Energy Sources and Responsive Demand. Do We Need Congestion Management in the Distribution Grid?* Power Systems, IEEE Transactions on 29, No. 5, pp. 2119-2128.

[79] Demiroren, A., and Yilmaz, U. (2010). *Analysis of change in electric energy cost with using renewable energy sources in Gökceada, Turkey - An island example.*

[80] Duic, N. and Da Gracia Carvalho, M. (2004). *Increasing renewable energy sources in island energy supply: case study Porto Santo.* Renewable and Sustainable Energy Reviews, Vol. 8, pp. 383–399.

[81] Enevoldsen, P. and Sovacool, B. (2016). *Integrating power systems for remote island energy supply; lessons from Mykines, Faroe islands.* Renewable Energy 85, pp. 642-648.

[82] Katsaprakakis, D. et al. (2009). *Electricity supply on the island of Dia based on renewable energy sources.*

[83] Krajacic, G., Duic, N. and Da Gracia Carvalho, M. (2009). *H2RES, Energy Planning tool for island energy systems - The case of the Island Mljet.* International journal of hydrogen energy, Vol. 34 pp. 7015–7026.

[84] Sakaguchi, T. and Tabata, T. (2015). *100% electric power potential of PV, wind power, and biomass energy in Awaji island Japan.* Renewable and Sustainable Energy Reviews, Vol. 15, pp. 1156-1165.

[85] Senjyu, T. et al. (2007). *Optimal configuration of power generating systems in isolated island with renewable energy.* Renewable Energy, Vol. 32, pp. 1917–1933.

[86] Yue, C., Chen, C., and Lee, Y. (2016). *Integration of optimal combinations of renewable energy sources into the energy supply of Wang-An Island.* Renewable Energy, Vol. 86, pp. 930-942.

[87] Harikumaran, J. (2012). *Sizing and Charge Control Strategies for a Grid-Connected Micro-grid with Electric Vehicles.* Delft University of Technology, Master Thesis.

[88] Qi, W. et al. (2011). *A distributed control framework for smart grid development - Energy/water system optimal operation and electric grid integration.* Journal of Process Control, Vol. 21, pp. 1504– 1516

[89] Weaver, W. et al. (2015). *Distributed control and energy storage requirement of networked DC microgrids.* Control Engineering Practice, Vol. 44, pp. 10–19.

[90] Bazmi, A. and Zahedi, G. (2011). *Sustainable energy systems: role of optimisation modeling techniques in power generation and supply - a review.* Renewable and Sustainable Energy Reviews, Vol. 15, pp. 3480–3500.

[91] Bernal-Augustín, J. and Dufo-López, R. (2009). *Simulation and optimisation of standalone hybrid renewable energy systems.* Renewable and Sustainable Energy Reviews, Vol. 13, No. 8, pp. 2111–2118.

[92] Verzijlbergh, R. and Lukszo, Z. (2011). *System Impacts of Electric Vehicle Charging in an Evolving Market Environment*. 2011 International Conference on Networking, Sensing and Control.

[93] De Souza Rebeiro, L. et al (2011). *Isolated micro-grids with renewable hybrid generation: The case of Lençóis island.* IEEE Transactions On Sustainable Energy, Vol. 2, No. 1, pp. 1-11.

[94] Ulsrud, K. et al (2011). *The Solar Transitions research on solar mini-grids in India: Learning from local cases of innovative socio-technical systems.* Energy for Sustainable Development, Vol. 15, No. 3.

[95] Kapsali, M. Anagnostopoulos, J. and Kaldellis, J. (2012). *Wind powered pumped-hydro storage systems for remote islands; a complete sensitivity analysis based on economic analysis.* Applied Energy, Vol. 99, Issue C, pp. 430-444.

[96] Bueno, C. and Carta, J. (2005). *Technical–economic analysis of wind-powered pumped hydrostorage systems. Part I: model development.* Renewable and Sustainable Energy Reviews Vol. 10, pp. 312–340.

[97] Bueno, C. and Carta, J. (2005). *Technical–economic analysis of wind-powered pumped hydrostorage systems. Part II: model application to the island of El Hierro.* Solar Energy, Vol. 78, No. 3, pp. 396-405.

[98] Pina, A., Baptista, P. and Silva, C. and Ferrão, P. (2014). *Energy reduction potential from the shift to electric vehicles: The Flores island case study.* Energy Policy Vol. 67, pp 37–47.

[99] Camus, C.,Farias T. and Esteves, J. (2011). *Potential impacts assessment of plug-in electric vehicles on the Portuguese energy market.* Energy Policy, Vol. 39, No. 10, pp. 5883-5897.

[100] Camus, C. and Farias, T. (2012). *The electric vehicles as a mean to reduce CO2 emissions and energy costs in isolated regions. The São Miguel (Azores) case study.* Energy Policy, Vol. 43, pp. 153-165.

[101] Denny, E. and Keane, A. (2013). *A Smart Integrated Network for an Offshore Island.* Proceedings of the IEEE, Vol. 101, No. 4, April 2013.

[102] Ilic, M., Xie, L., and Liu, Q. (c-eds) (2013). *Engineering IT-Enabled Sustainable Electricity Services: The Tale of Two Low-Cost Green Azores Islands.* Springer: August 2013.

[103] Bunker, K. (2015). *A Caribbean Island Says Goodbye Diesel and Hello 100% Renewable Electricity.* Retrieved from: http://blog.rmi.org/blog_2015_01_07_a_caribbean_island_says_goodbye_to_diesel_fuel

[104] Centraal Bureau voor de Statistiek (2016). Retrieved from: https://www.cbs.nl/en-gb/news/2016/29/population-caribbean-netherlands-stable

[105] Van Weijsten, B. (2016). Interview energieconsultant Bart van Weijsten. April 7, 2016

[106] Caribbean Journal (2016). Retrieved from: http://www.caribjournal.com/2016/05/09/the-caribbeans-richest-countries/#

[107] Utilities Aruba (2014). Retrieved from: Utilities-Aruba-Corporate-Report-June-2014-by-The-Report-Company

[108] WEB Aruba (2016). Retrieved from: http://www.webaruba.com/renewable-energy-dashboard/aruba

[109] TNO Aruba (2016). Retrieved from: https://www.tno.nl/en/focus-area/energy/sustainable-energy/new-markets-and-users/smart-community-aruba/

[110] National Renewable Energy Laboratory (2014). *Aruba Energy Snapshot.*

[111] Acevedo, D. (2016). S*ustainable Energy for Small Islands: Aruba's road to 100% Sustainable Energy.* Delft University of Technology, Master Thesis.

[112] Carbon War Room (2013). *Smart Growth Pathways: Building a Green Platform for Sustainable Aruba.*

[113] WEB Aruba (2016). Retrieved from: http://www.webaruba.com/energy-production/power-production-figures

[114] National Renewable Energy Laboratory (2015). *Curacao Energy Snapshot.*

[115] Centraal Bureau voor de Statistiek (2016). Retrieved from: http://cbs.aw/wp/

[116] Visit Aruba (2016). Retrieved from: https://www.visitaruba.com/traveling-to-aruba/when-to-travel/

[117] Lopez, M. (2016). Personal email Melanie Lopez Technical/Sustainability Advisor WEB Aruba N.V. 21-9-2016

[118] Boekhoudt, O. (2011). *Green Energy in Aruba*. Green Aruba Conference 2011.

[119] Ras, F. (2016). Interview Francis Ras, Manager Technical Affairs, WEB Aruba N.V. September 8, 2016

[120] WEB Aruba (2016). *Corporate strategy: Our roadmap to sustainability.* Retrieved from: http://www.webaruba.com/our-company/corporate-strategy

[121] Langstaff, M. and Gomez, N. (2012). *Intermittent Renewable Electricity: Incentivizing Load Management Technologies in Aruba.* Harvard University Working Paper.

[122] PMO Aruba (2016). Retrieved from: http://www.pmoaruba.com/vision/sustainable-energy/

[123] Department of Energy (2015). *Global Energy Storage Database.* Retrieved from: http://www.energystorageexchange.org/projects/global_search?q=aruba

[124] Knegt L. and Moons, R. (2014). E*lektrische auto's en het reduceren van transport-gerelateerde CO2-emissies op Aruba.* TNO-rapport, 25 juni 2014.

[125] Elmar (2014). *Elmar: Electric Vehicle Integration and Impact on the Electric Grid*.

[126] Union of Concerned Scientists (2016). *Questions and Answers on Storage and Vehicle Charging as Renewables Arrive.* Retrieved from: http://smartgrid.ieee.org/resources/webinars/past-webinars?eid=61&m=d7ad069d3940ebcaaf9ce65812521293

[127] Ecomento (2015). Retrieved from: http://ecomento.com/2015/03/19/buyers-guide-used-nissan-leaf/

[128] Lampe-Chiquito, R. (2016). Interview Rubiela Lampe-Chiquito, CEO Activated Power, Aruba.

[129] California Indepedent System Operator (2016). Southern California Edison Electricity Provider CAISO.

[130] Howey, D., Martinez-Botas, R., Cussons, B. and Lytton, L. (2011). *Comparative measurements of the energy consumption of 51 electric, hybrid and internal combustion engine vehicles.* Transportation Research Part D, Vol. 6, pp. 459-464.

[131] Headley, O. (1997). *Renewable Energy in the Caribbean.* Solar Energy, Vol. 59, No. 1-3, pp. 1-9.

[132] Van der Meulen, M. (2012). *The geothermal option*. In Green Aruba Conference III, 2012.

[133] Cornett, A. (2008). *A global wave energy resource assessment.* International Society of Offshore and Polar Engineers, Vol. 18, pp. 318–326.

[134] National Aeronautics and Space Administration (2006). *Topex/poseidon: Revealing hidden tidal energy.*

[135] Osorio, A., Arias-Gaviria, J., Devis-Morales, A., Acevedo, D., Velasquez, H. and Arango-Aramburo, S. (2016). *Beyond electricity: The potential of ocean thermal energy and ocean technology ecoparks in small tropical islands.* Energy Policy, Vol. 98, pp. 713-724.

[136] Arends, R. (2016), Interview Richard Arends, Chief of Staff, National Government of Aruba. September 7, 2016

[137] Meteonorm (2015). *Global Meteorological Database, version 7.*

[138] Koninklijk Nederlands Meteorologisch Instituut (2016). Retrieved from: http://projects.knmi.nl/hydra/meta_data/dir_codes.htm

[139] HOMER Energy (2012). *HOMER MODEL: Cost of Electricity Based on Renewable Penetration.*

[140] National Climate Data Centre (2016). Retrieved from: https://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=hourly&layers=1

[141] Gioutsos, D. (2016). *Determination of Cost-Optimal Electricity System Configurations for the Transition to Sustainable Energy Systems on Islands*. Delft University of Technology, Master Thesis.

[142] Swapnil, D. et al. (2013). *Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review.* Energy Procedia, Volume 33, 2013, Pages 311-321.

[143] Dolara, A. et al (2015). *Comparison of different physical models for PV power output prediction.* Solar Energy, Vol. 119, pp. 83-99.

[144] Luque, A. and Hegedus, S. (2013). *Handbook of Photovoltaic Science and Engineering, Second Edition.* Wiley & Sons Ltd, Chichester, England.

[145] Evans, D. and Florschuetz, L. (1977). *Cost studies on terrestrial photovoltaic power systems with sunlight concentration.* Solar Energy, Vol. 19, pp. 255-26.

[146] Green, M. et al. (2014). *Solar cell efficiency tables*. Progress in Photovoltaics, Vol. 23, Issue 1, pp. 1–9.

[147] Chang, C. and Cheng, H. (2012). *A High-Efficiency Solar Array Simulator Implemented by an LLC Resonant DC-DC Converter.* IEEE Transactions on Power Electronics, Vol. 28, pp. 3039- 3046.

[148] SolarGIS (2011). *Description of methods implemented in SolarGIS pvPlanner.* GeoModel Solar s.r.o., pvplanner algorithms - solargis version 1.6 ed., 2011.

[149] Burger, B. and Kranzer, D. (2009). *Extreme high efficiency PV-power converters.* Power Electronics and Applications, 13th European Conference on Power Electronics and Applications.

150] Vestas (2016). Vestas V90 3 MW power curve. Retrieved from: http://www.vestas.com/en/products/turbines/v90%203_0_mw#!power-curve

[151] Manwell, J., McGowan, J. and Rogers, A. (2013). *Wind Energy Explained: Theory, Design and Application, 2nd Edition.* Wiley & Sons Ltd, Chichester, England.

152] Nelson, V. (2013). *Wind Energy: Renewable Energy and the Environment, Second Edition.* CRC Press, Boca Raton, USA.

[153] Robinson, J., Jovcic, D. and Geza, J. (2010). *Analysis and Design of an Offshore Wind Farm Using a MV DC Grid.* IEEE Transactions on Power Delivery, Vol. 25, pp. 2164- 2173.

[154] Gopalakrishnan D., Van Essen, H., Kampman, B. and Grünig, M. (2011). *Impacts of Electric Vehicles - Deliverable 2. Assessment of electric vehicle and battery technology.* CE Delft.

[155] Pasaoglu, G. Fiorello D., Zani L., Martino A., Zubaryeva A. and Thiel C. (2013). *Projections for Electric Vehicle Load Profiles in Europe Based on Travel Survey Data.* European Commission Joint Research Centre Institute for Energy and Transport.

[156] Van Haaren, R. (2011). *Assessment of Electric Cars' Range Requirements and Usage Patterns based on Driving Behavior recorded in the National Household Travel Survey of 2009.* Solar Journey USA.

[157] Sociaal en Cultureel Planbureau (2009). Mobiliteitsonderzoek Nederland 2009. Retrieved from: https://www.scp.nl/Onderzoek/Bronnen/Beknopte_onderzoeksbeschrijvingen/Mobiliteitsonderzoek_Nederland_MON

[158] Diouf, B. and Pode, R. (2015). *Potential of lithium-ion batteries in renewable energy.* Ren. Energy Vol. 76, pp. 375–380

[159] Battery University (2016). Retrieved from: http://batteryuniversity.com/

[160] WEB Aruba (2014). *E-Bus Pilot Project. Operated by ARUBUS – Powered by WEB.* Company presentation.

[161] Dogger, J., Roossien, B. and Nieuwenhout, F. (2010). *Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage.* IEEE Transactions on Energy Conversion, Vol. 26, pp. 256- 263.

[162] Morrison, P., Binder, A., Funieru, B., Sabirin, C. (2009). *Drive train design for medium-sized zero emission electric vehicles.* 13th European Conference on Power Electronics and Applications.

[163] Lampe, E. (2016). Interview Elthon Lampe, Business Development Officer, ELMAR N.V. 5-9-2016

[164] De Brey, B. (2015). *10 Learnings for governments & organisations to make EV a success.* Stedin and ELaad.

[165] Renewable Energy Advisors (2016). *What is LCOE?* Retrieved from: http://www.renewable-energy-advisors.com/learn-more-2/levelized-cost-of-electricity/

[166] Ueckerdt, F., Hirth, L., Luderer, G., and Edenhofer, O. (2013). *System LCOE: What are the costsof variable renewables?* Energy, vol. 63, pp. 61–75.

[167] WEB Aruba (2015). Financial report 2015. Retrieved from: http://www.webaruba.com/sites/default/files/pdf-files/2015.03%20Online%20report%201st%20Quarter%202015_0.pdf

[168] Cannon, M. (2016). *Model Predictive Control*. Oxford University, England. Retrieved from: https://www.researchgate.net/file.PostFileLoader.html?id=57a30a3148954c1f7c3b7abb&assetKey=AS%3A391292329709580%401470302769414

[169] Rocky Mountain Institute (2014). *Four Reasons Why Natural Gas is the Wrong Choice for Electricity in the Caribbean.* Retrieved from: http://blog.rmi.org/blog_2014_10_23_four_reasons_why_natural_gas_is_wrong_for_electricity_in_the_caribbean

[170] Rocky Mountain Institute (2014). *Pulling Back the Veil on EV Charging Station Costs.* Retrieved from: http://blog.rmi.org/blog_2014_04_29_pulling_back_the_veil_on_ev_charging_station_costs

[171] Nationaal Kennisinstituut Laadinfrastructuur (2016). *Verslag Workshop Benchmark Kosten Publieke Laadinfrastructuur.* Retrieved from: http://nklnederland.nl/uploads/files/Verslag_workshop_Benchmark_Kosten_Publieke_Laadinfrastructuur_2016.pdf

[172] Kempton, W., et al. (2008). *A Test of Vehicle-to-Grid (V2G) for Energy Storage and Frequency Regulation in the PJM System. Results from an Industry-University Research Partnership.*

[173] Chandra Mouli, G.R. (2016). Personal email Gautham Ram Chandra Mouli, PhD TU Delft.

[174] Gagnon, L., Belanger, C., and Uchiyama, Y. (2002). *Life-cycle assessment of electricity generation options: The status of research in year 2001*. Energy Policy, Vol. 30, pp. 1267–1278.

[175] Nugent, D. and Sovacool, B. (2002). *Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey.* Energy Policy. Vol. 65, pp. 229–244

[176] Sullivan, J. et al. (2004). *CO2 emission benefit of diesel (versus gasoline) powered vehicles.* Environ. Sci. Technol. Vol. 38, pp. 3217–3223.

[177] Lukszo, Z. (2015). *Dynamic optimisation.* Part of course Engineering Optimisation, TU Delft.

[178] Bradley, S. et al. (1977). *Applied Mathematical Programming.* Addison-Wesley. Retrieved from: http://web.mit.edu/15.053/www/

[179] Carter, M. (2001). *Foundations of Mathematical Economics.* MIT Press, Cambridge, USA.

[180] Bellman, R. (1957). *Dynamic Programming.* Princeton University Press, Princeton, USA.

[181] Eriksson,L. (2016). *Deterministic Dynamic Programming and Some Examples.* Vehicular Systems, Linköping University. April 19, 2016.

[182] Martin, R., Rardin, L.,and Campbell, B. (1990). Polyhedral characterization of discrete dynamic programming. Operations Research, Vol. 38, pp. 127-138.

[183] Raffensperger, J. (1970). The Marriage of Dynamic Programming and Integer Programming. PhD thesis, University of Canterbury, Christchurch, New Zealand.

[184] Buyuktahtakin, E. (2016). Dynamic Programming Via Linear Programming. Wiley Encyclopedia of Operations Research and Management Science.

[185] Peterson, S., Apt, J. and Whitacre, J. (2010). Lithium-ion battery cell degradation resulting from realistic vehicle and vehicle-to-grid utilization. Journal of Power Sources, Vol. 195, pp. 2385–2392.

[186] Derix, R. (2013). Traffic between school, work and home in Aruba in 2010. The geography of household destinations. Central Bureau of Statistics ARUBA. Environmental Statistics.

LIST OF ACRONYMS

AC	Alternating Current
ACR	Automatic Centralized Response
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
AWG	Aruban Guilder / Arubaanse florin
BAU	Business-As-Usual
BEV	Battery Electric Vehicle
CC	Constant Current
CV	Constant Voltage
COP21-UNFCC	21st Conference of Parties to the United Nations Framework Convention on Climate Change
CTO	Chief Technology Officer
CWR	Carbon War Room
DC	Direct Current
DoD	Depth Of Discharge
DP	Dynamic Programming
DSM	Demand Side Management
ELMAR	ELectrische Maatschappij Aruba (grid operator utility)
EU	European Union
EV	Electric Vehicle
FCCA	Fundacion Cas Pa Comunidad Arubano (housing company Aruba)
FEV	Full Electric Vehicle
G4V	Grid-for-vehicle (one-directional controlled charging)
GDP	Gross Domestic Product
GHG	Greenhouse Gas
HEV	Hybrid Electric Vehicle
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
ID	Identification Number
INDC	Intended Nationally Determined Contributions
IP	Integer Programming
ISD	Integrated Surface Database
LCOE	Levelised Cost Of Electricity

LD	Light-Duty
LNG	Liquefied Natural Gas
LOLE	Loss Of Load Expectation
LPG	Liquefied Petroleum Gas
LRMC	Long Run Marginal Cost
MPC	Model Predictive Control
MSW	Municipal Solid Waste
NCDC	National Climatic Data Center (USA)
NKL	Nationaal Kennisinstituut Laadinfrastructuur (Netherlands)
NOAA	National Oceanic and Atmospheric Administration (USA)
NREL	National Renewable Energy Laboratory (USA)
O&M	Operation & Maintenance
OTEC	Ocean Thermal Energy Conversion
PHEV	Plug-in Hybrid Electric Vehicle
PHS	Pumped Hydro Storage
PV	Photovoltaic
RES	Renewable Energy Sources
RMI	Rocky Mountain Institute
SETAR	Communication company on Aruba
SIS	Solar Integrated Storage
sLCOE	System Levelised Cost Of Electricity
sLC	System Levelised Cost
SOC	State Of Charge
SUV	Sport Utility Vehicle
SWEGS	Single Well Enhanced Geothermal Systems
TNO	Nederlandse Organisatie voor Toegepast-natuurwetenschappelijk onderzoek (Netherlands)
TPP	Thermal Power Production
TSO	Transmission System Operator
UN	United Nations
USD	United States Dollar
V2G	Vehicle-to-Grid (bi-directional controlled charging)
V2X	Vehicle-to-Miscellaneous
WEB	Water- En Energiebedrijf Aruba (power production utility)