

An analysis of options for a sustainable Texel

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An analysis of options for a sustainable Texel

Laura Patricia Mc Kula
Gutiérrez
January, 2015



EINDHOVEN UNIVERSITY OF TECHNOLOGY
Stan Ackermans Institute
SMART ENERGY BUILDINGS & CITIES

An analysis of options for a sustainable Texel

By

Laura Patricia Mc Kula Gutiérrez

A dissertation submitted in partial fulfillment of
the requirements for the degree of
Professional Doctorate of Engineering

Prof. ir. Wil L. Kling, university coach
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Abstract

The need to reduce energy consumption and to increase the energy generation from renewable resources is imminent. The community of the Dutch island of Texel has the ambition to be part of this energy transition towards sustainability and has adopted the goal of becoming fully sustainable by the year 2020 [1]. To achieve this, some projects are already taking place and Alliander is assessing the different strategies related to the grid management to maximize the level of energy neutrality with lower investment costs as part of the “Proeftuin Texel” project.

This study continues the analysis of the “Proeftuin Texel” to identify the optimal solutions for the creation of a sustainable energy system. The study has two main objectives. The first objective is to calculate the maximum installed capacity of renewable energy sources (RES) technologies by optimizing the use of the current infrastructure; the second is to assess the benefits of energy balancing solutions. These solutions include heat pumps, electrical vehicles, and an energy management system (EMS). Three scenarios are created and the benefits are measured in terms of cost per reduction of CO₂ emissions for each scenario. The results from this study could serve as a reference for energy related decisions in Texel and could be adapted to other cases.

The three scenarios are composed by the following solutions: the first scenario analyses the maximum capacity of the actual grid to implement PV panels; the second scenario adds wind turbines and alternative solutions for the use of the actual grid; and in the third scenario the electricity consumption is increased by electrifying the residential heating and private transport to add flexibility on the demand side and balance it with the EMS.

The results show that the greater benefits are achieved by the second scenario, while the benefits of the first and those of the third (in comparison with the second scenario) are notable lower; consequently their costs per tonne of CO₂ reduction are higher. A further analysis shows the effect from each solution of the three scenarios, showing that the lower cost solutions are wind turbines combined with the grid solutions consisting on cable-pooling and the use of the backup installation. From this study it can be concluded that for this case with the given timeframe, a smart design is more effective than a smart grid.

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And finally, thanks to my husband Sjon, and my family for their never-ending love and support.

Patricia Mc Kula

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Chapter 1. Introduction and background

1.1. Introduction

The need to reduce the energy consumption and increase the energy generation from renewables and/or sustainable resources is imminent. Nowadays there are several projects going on towards this goal on different levels such as buildings, neighborhoods and cities. Participation from all stakeholders is needed and the sustainability of the scaled and long term impacts of these projects should be assessed.

The community from the Dutch island of Texel has the initiative to be part of this energy transition and they adopted the goal of becoming fully sustainable by the year 2020 [2]. For this purpose, some projects are already taking place, for example “Cloud Power”, which is developed by TexelEnergie, Capgemini and Alliander. This project aims to reduce energy consumption and encourage renewable energy sources (RES) conversion by implementing a domestic energy management system; at the same time, as a side analysis, Alliander is assessing the different solutions and strategies related to the grid management to maximize the level of energy neutrality with lower investment costs as part of the “Proeftuin Texel” project.

This project will complement and continue the analysis of the “Proeftuin Texel” whose objective is to assess the benefits of the sustainable energy solutions. The assignment has two main objectives. The first objective is to calculate what would be the maximum installed capacity of RES technologies optimizing the use of the current infrastructure. The second objective is to assess the benefits of energy balancing solutions, including an Energy Management System (EMS), in order to optimize the overall energy system. The benefits will be measured in terms of cost per reduction of CO₂ emissions for each solution. The results from this study could serve as a reference for the energy related decisions in Texel and could be adapted to other cases.

1.2. Sustainable approach to energy neutrality

Based on the “Energie neutral ontwikkeling Locatie Valkenburg” [3], an area is considered to be energy neutral if, annually, its net import of fossil or nuclear energy from outside of the system is zero. This concerns the building-related and non-building-related energy requirements, e.g. for public lighting and pumps. This means that the energy consumed is equal to the amount of renewable energy conversion within the area, in a year. The energy solutions may be situated up to 10 km outside the area’s boundaries, subject to all parties’ acceptance.

Even if energy neutrality is seen as a path towards sustainability, this is not always the case. The ambitious goal of becoming energy neutral could have negative impacts in the long term and excessive undesirable costs if the solution proposed does not consider the whole system, and if it does not take into account each stakeholder’s capacities and requirements [4].

Increasing the generation of a region’s distributed energy might necessitate expansion of the grid’s capacity to import and export energy. The investment for such change could be very high and would also make the region more dependent on the outside. In order to have a more sustainable approach, in this assessment the integral solution has to optimize the use of the existing grid, avoiding major modifications, and the annual CO₂ emissions reductions will be calculated and compared to the cost of each solution.

1.3. Ongoing projects at Texel

Several analyses and projects are being made to explore the island possibilities. One example is Jacco Jochemsen’s report “Texel’s future energy management” [5], this study assesses three theoretical scenarios for different energy sources (i.e. 100% wind, 100% PV and 100% tidal) to have an idea of what could be the impact of this development. Alliander, together with TexelEnergie and Capgemini, are part of another project called the “Cloud Power”. This is a two year pilot project that is to be completed at the end of 2014. Its goal is to reduce the energy consumption and locally generate the required energy from RES [6].

The three main targets of the “Cloud Power” are: [7]:

- a) Facilitate local RES, and encourage the community participation.
- b) Monitor and provide insight of energy consumption and conversion to the individual prosumers.
- c) Provide dynamic energy tariffs to the electricity consumers and evaluate its impact.

As part of this, Alliander is developing the project “Proeftuin Texel” assessing the level of energy neutrality that can be achieved by optimizing the current energy grids.

The focus of the “Proeftuin Texel” is to provide a realistic and sustainable approach to Texel regarding their ambitious energy goals. The outcome of the project is a set of smart and affordable alternatives for the near future that will bring Texel some steps further towards their goals.

The project is being developed in three phases increasing the complexity of the energy system and the level of energy neutrality without making major changes to the current electricity grid. The three phases are explained in section 3.2. The project “An analysis of options for a sustainable Texel” will merge and complement this analysis.

1.4. General characteristics of Texel

Texel is a municipality in the province of North Holland. The location of North Holland and Texel in The Netherlands is shown in Figure 1 and Table 1 lists relevant information of the island.

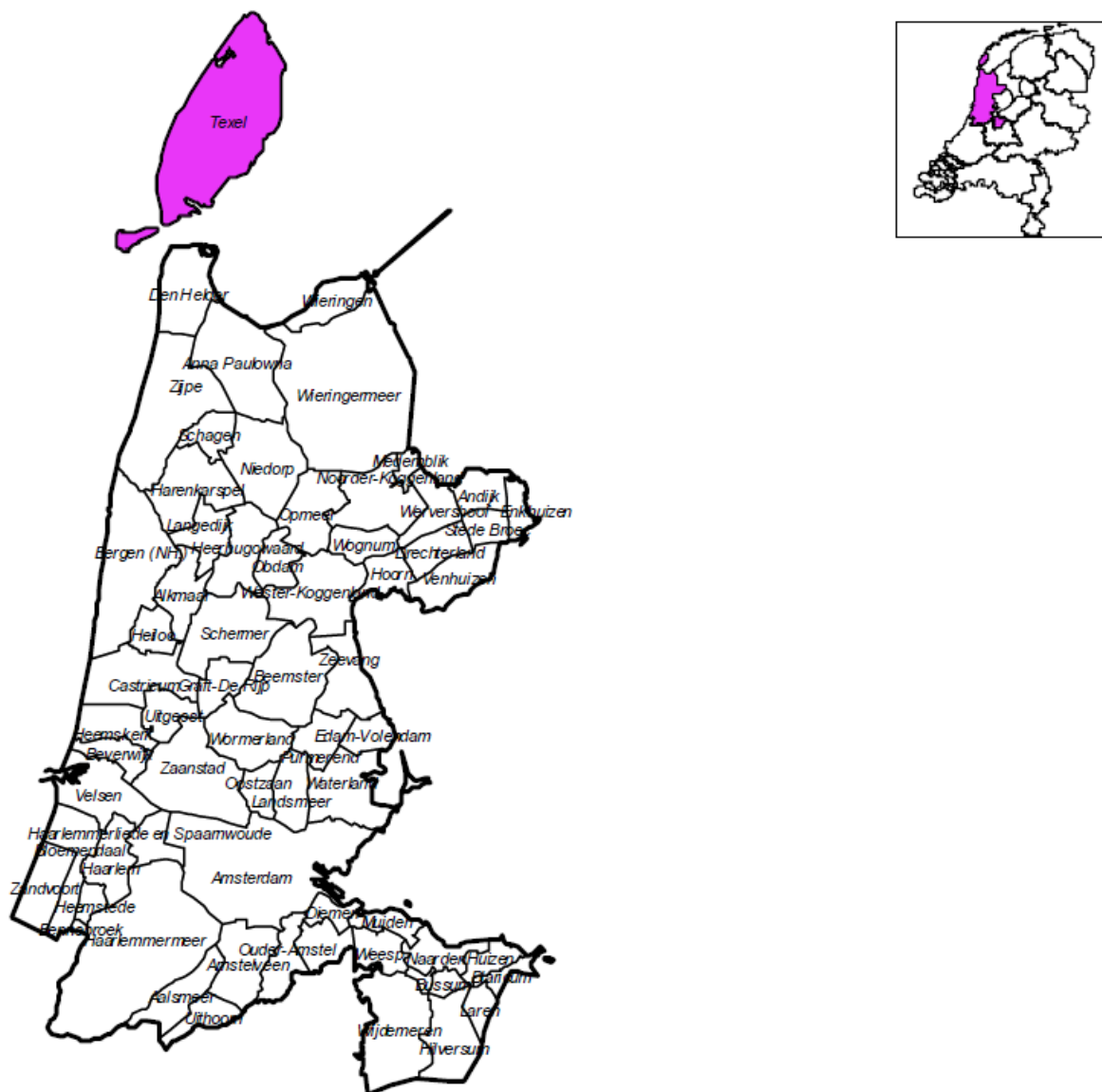


Figure 1. Map of North Holland [8]

Table 1. Texel's facts

| | | Source |
|------------------------------|---------------|-------------|
| Land [km²] | 161 | [9] |
| Habitants | 13.662 | [9] |
| Private houses | 6050 | [10] |
| Holiday houses | 3230 | [10] |
| Companies | 1240 | [8] |
| Personal cars | 5677 | [8] |
| Company cars | 1743 | [8] |
| Motorcycles | 666 | [8] |

1.5. Characteristics of the electricity grid

The capacity of Texel to export and import electricity is set by the current connection between the island and the mainland. The connection consists basically of two cables of 29 MVA and two 50/10 kV transformers of 18 MVA as shown in

Figure 2 [4].

The increase of green electricity production might result on an increase of electricity exchange with the exterior, if no further actions are taken. The outcome will be higher electricity dependence and excessive investment costs to increase the grid capacity.

The analysis made on the Phase I from the "Proeftuin Texel" project [4] showed that the 18 MVA transformers are the bottleneck of Texel's electricity grid to import and export electricity because their capacity is not only smaller than the capacity of the cables but also of the nine medium voltage regions existing on the island.

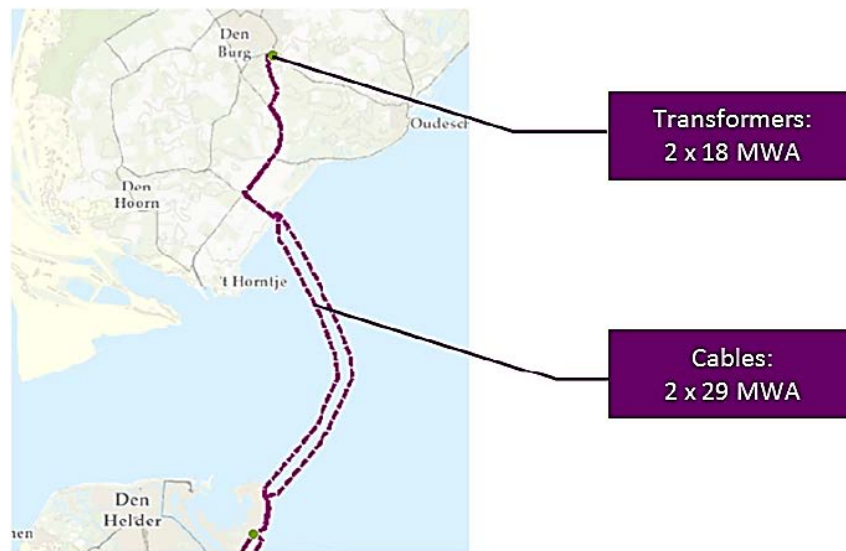


Figure 2. Main components of electricity connection between Texel and the mainland [4].

The available grid capacity inside the island was also analyzed. As mentioned before, there are nine medium voltage fields in Texel, and all together they have 33 MW available. The grid capacity availability per field is shown in Figure 3.

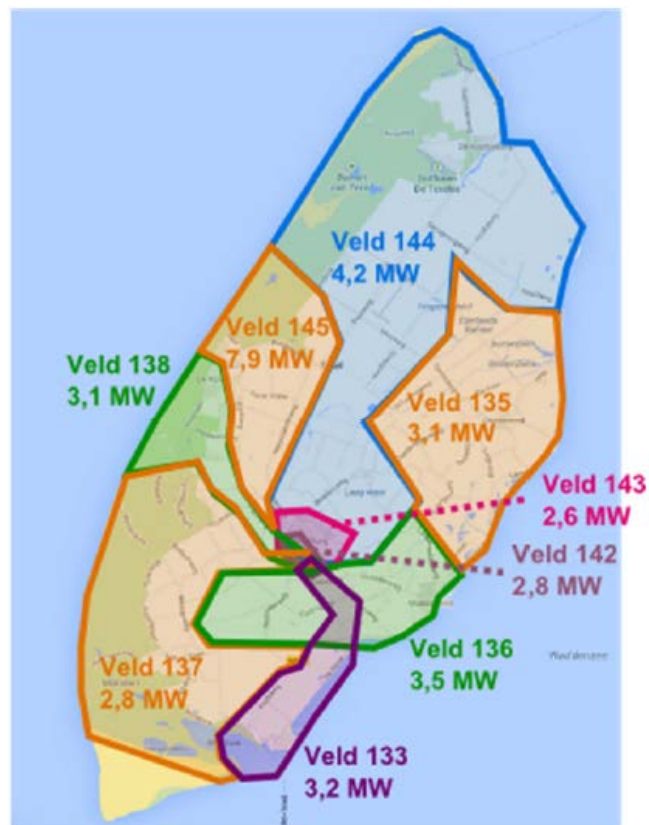


Figure 3. Available power capacity of the nine medium voltage regions [4].

1.6. Texel's energy consumption

The annual energy consumption in Texel is 1,93 PJ. All energy is imported; the proportion of type of energy and use is shown in Figure 4 and Figure 5, and the breakdown of the annual energy supply and consumption of the island is presented in Table 2.

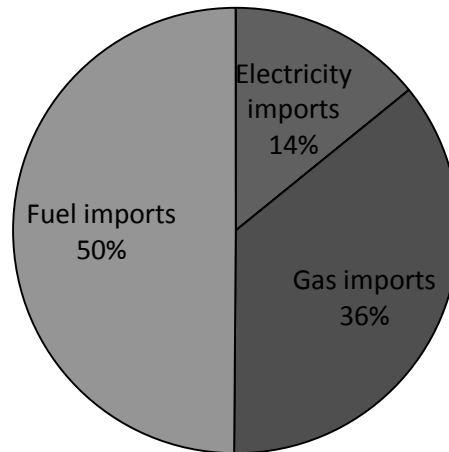


Figure 4. Energy imports in Texel [10] [11], percentages shown represent: energy source/total energy (1,93 PJ).

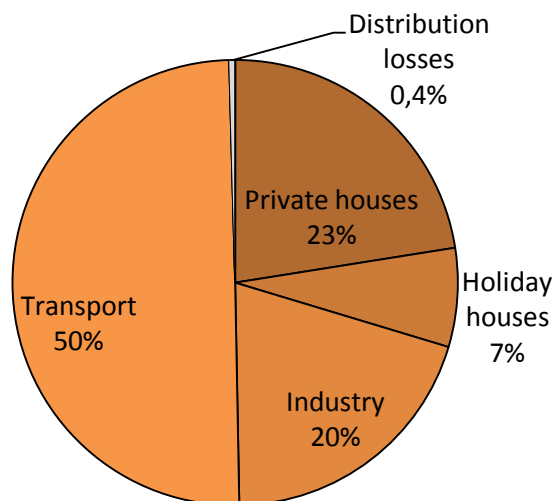


Figure 5. Energy use in Texel [10] [11], percentages shown represent: energy per type of use/total energy (1,93 PJ).

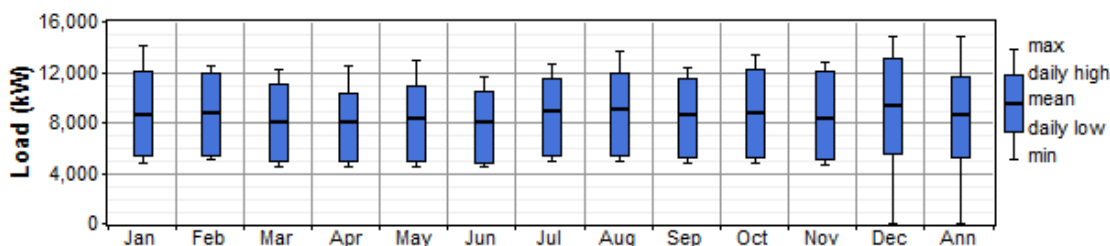
Table 2. Texel's 2009 Energy Balance [10] [12].

| SUPPLY AND CONSUMPTION [TJ] | Elec. | Gas | Gasoline | Diesel | Total |
|--------------------------------------|--------------|------------|-----------------|---------------|--------------|
| Imports | 274 | 695 | 297 | 667 | 1933 |
| TOTAL ENERGY SUPPLY | 274 | 695 | 297 | 667 | 1933 |
| Distribution Losses | -8 | | | | -8 |
| TOTAL FINAL CONSUMPTION | 265 | 695 | 297 | 667 | 1924 |
| INDUSTRY SECTOR | 129 | 258 | - | - | 387 |
| Other business use / unknown | 4 | 6 | | | 9 |
| Services and trade | 55 | 92 | | | 147 |
| Industry, logistics and construction | 12 | 28 | | | 40 |
| Agriculture, Livestock and Fisheries | 11 | 21 | | | 32 |
| Education, sport and government | 2 | 7 | | | 9 |
| Hospitality and Tourism | 46 | 105 | | | 151 |
| TRANSPORT SECTOR | | | 297 | 667 | 964 |
| Road Private Transport | | | 149 | | 149 |
| Road Business Transport | | | 149 | | 149 |
| Ferry | | | | 151 | 151 |
| Fishery | | | | 515 | 515 |
| RESIDENTIAL SECTOR | 136 | 437 | | | 573 |
| Private Houses | 103 | 332 | | | 435 |
| Appliances | 103 | | | | 103 |
| Space heating | | 267 | | | 267 |
| Hot water | | 56 | | | 56 |
| Cooking | | 8 | | | 8 |
| Holiday Houses | 33 | 106 | | | 139 |

1.6.3. Electricity consumption in Texel

Based on the measurements taken at the substation, the annual energy consumption of Texel in 2009 is 76 GWh/year. The breakdown is shown in Table 2.

The peak power is 14,82 MW and the average daily consumption is 208 MWh/d. See the monthly power profile in Figure 6 and the average daily profile in Figure 7.

**Figure 6. Texel's monthly electricity profile.**

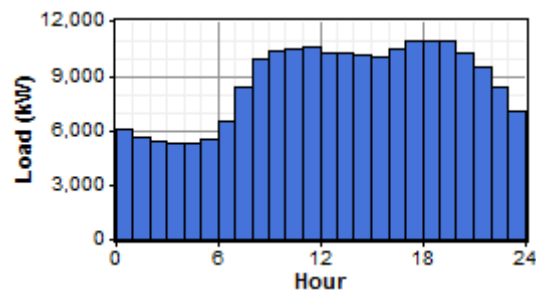


Figure 7. Texel's average daily electricity profile.

The electricity price considered for calculations is a single tariff of €0,06 per kWh [13]; this is the tariff from TexelEnergie before Taxes. And based on [14] the emissions of the electricity mix of the Netherlands the CO₂ emissions are of 0,455 kg of CO₂ /kWh.

1.7. Sun and wind availability

The information for the incident irradiance and wind availability used for the analysis was obtained from the “Koninklijk Nederlands Meteorologisch Instituut”, it corresponds to the data from de Koog from 2010.

1.7.1. Incident irradiance

The annual average radiation based on [15] is 2,99 kWh/m²/d. The monthly solar irradiance is shown in Figure 8, and the daily average solar radiation per month in Figure 9.

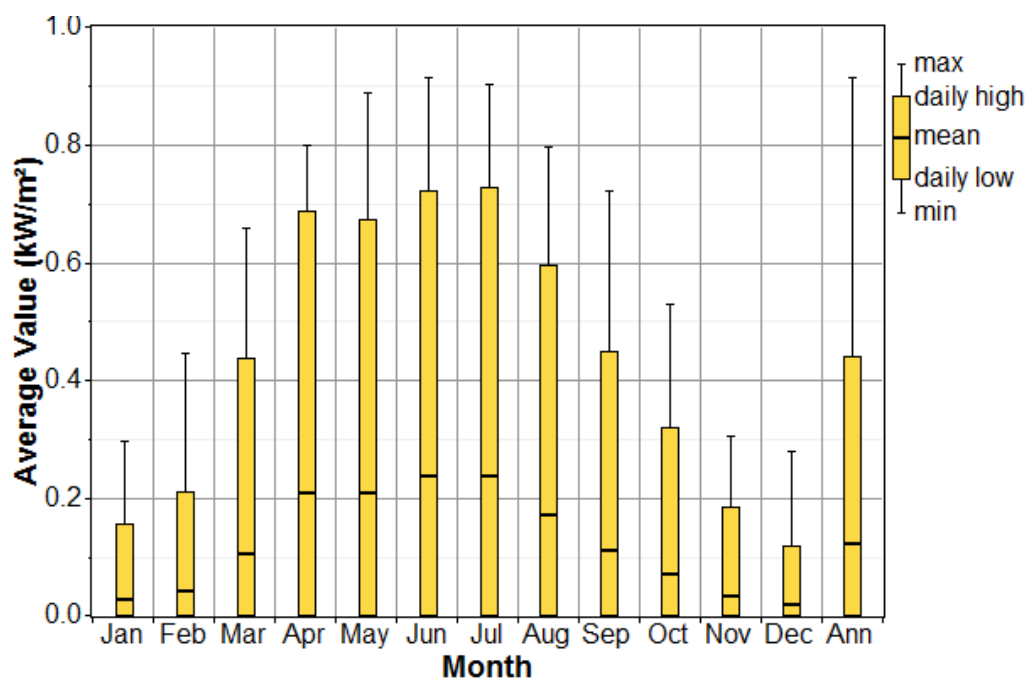


Figure 8. Monthly average of daily radiation in Texel [15].

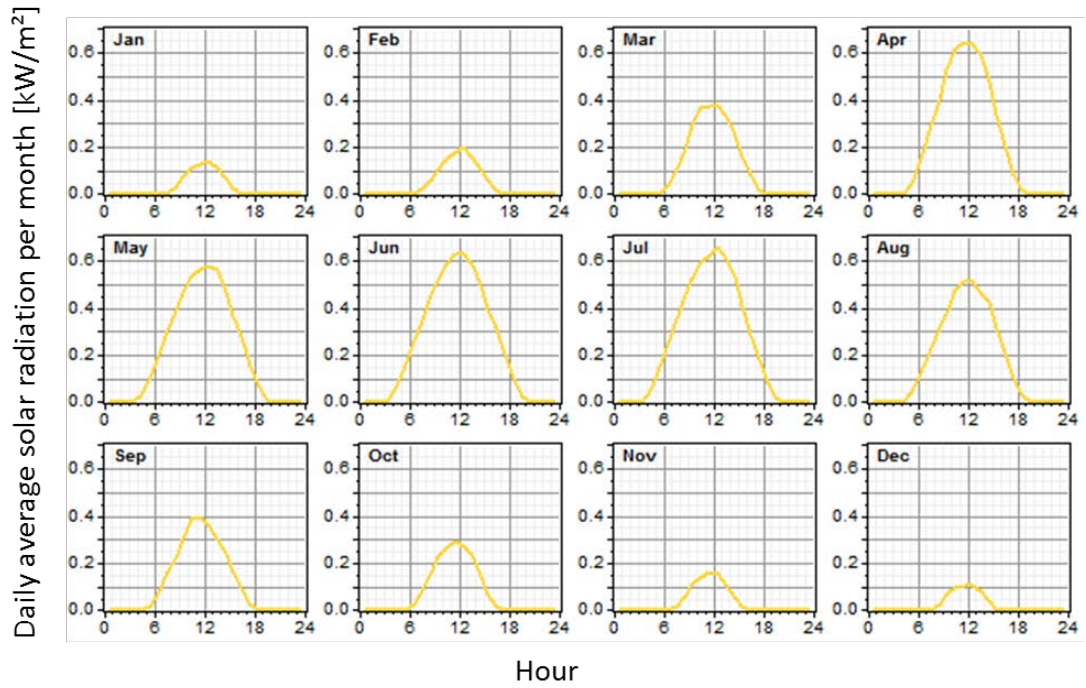


Figure 9. Daily average solar radiation per month [15].

1.7.2. Wind availability

The annual average wind speed based on [15] is 5,04 m/s. See Figure 10 for the monthly average wind speed, and the daily average wind speed per month in Figure 11.

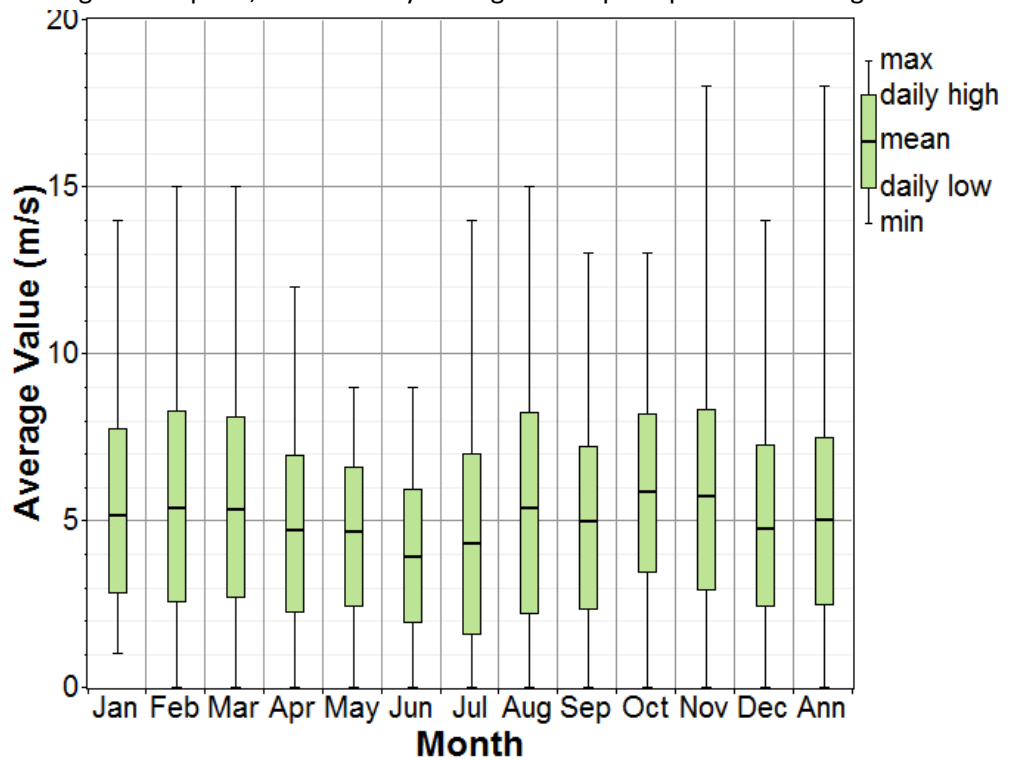


Figure 10. Monthly average wind speed of Texel [15].

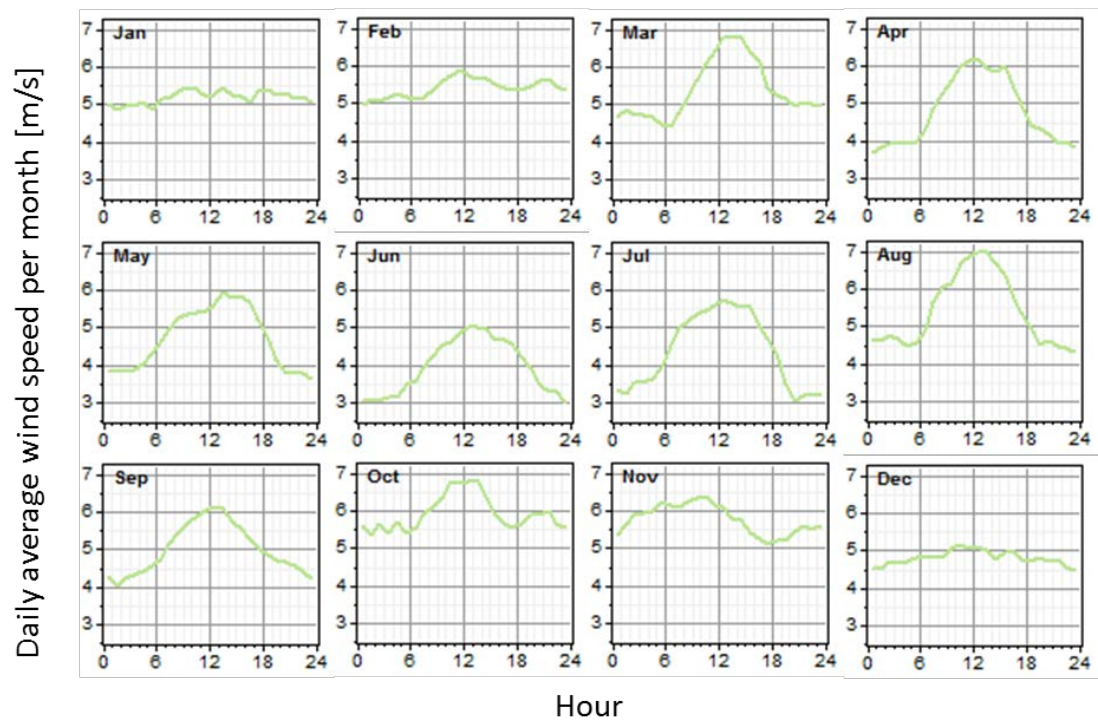


Figure 11. Daily average wind speed per month [15].

Chapter 2. Problem description

The objective of this project is to assess the benefits in terms of cost per CO₂ emissions reduction in Texel by implementing RES technologies and other solutions that facilitate energy balancing. The solutions are focused on optimizing the use of the current energy grids and increasing the share of renewable energy.

The main research question for this project is:

What are the cost and benefits of sustainable energy solutions in terms of cost per CO₂ reduction aiming to achieve an optimal energy system for Texel

As mentioned before this project complements the projects that are currently taking place at Alliander regarding the sustainability of the energy system in Texel. The purpose is to go one step further to come up with an optimal design at the energy system level, to serve as a vision of what can be achieved in the island without major investments in the current energy grids.

This area of study has clear physical boundaries and this could bring the opportunity to reproduce the proposed energy system in a larger scale. Other advantages of the project are that the sustainable initiative comes from the community and that actions are already taking place towards this goal. These factors could facilitate the stakeholders' cooperation and the data availability.

The analysis is made from the societal point of view; assessing the overall impact of the measures, that is not from any specific stakeholder's point of view. Therefore, external factors, such as taxes and subsidies, are left out of the study. The results of this study could serve as a reference for the potential impact of the decisions that are already taking place regarding the energy consumption and conversion of Texel, and will show opportunities of collaboration to Alliander. The findings can be adapted to other situations for the implementation of similar projects in other areas.

Chapter 3. Scope and methodology

The development of this assignment will take place mostly at Alliander to have close contact with the teams involved on related projects. The data will be obtained from the ongoing projects “Cloud Power” and “Proeftuin Texel” and the impact assessment will be done with the modeling software “Homer”, Matlab and the D-cision “Gebiedsmodel” tool, which uses a simple approach to come up to high level results of the impacts of the implementation of renewable energy conversion in an area.

3.1. Scope

The functional unit for the assessment is €/t of CO₂ emissions reduction. The results will be presented in an abatement curve showing the benefits per solution. For each solution, the quantity of CO₂ reductions will be calculated by doing the energy balance for each scenario and compare it with the base case, shown in Table 2. The total CO₂ emissions per scenario are a result of the emissions of all the energy imports minus the equivalent emissions from the electricity exported from RES. The CO₂ emission factors for each energy carrier are listed in Table 3.

Table 3. CO₂ emissions factor per energy carrier

| | CO ₂ emissions/TJ | Source |
|--------------------|------------------------------|-------------|
| Electricity | 126 | [14] |
| Gas | 56 | [16] |
| Gasoline | 72 | [16] |
| Diesel | 74 | [16] |

The proposed solutions must make an optimal use of the current energy grids, considering specially that an increase of the capacity of the connection with the mainland might result in undesirable high investments. Besides limiting the capacity of electricity import and export encourages a more sustainable energy behavior. The bottleneck of the current infrastructure are the two 18 MVA transformers on the connection with the mainland, other main grid characteristics are described in section 1.5.

The assessment will include the direct energy use by private, holiday and commercial buildings, and for transport, but the indirect energy use, water consumption, waste treatment are out of frame. See Table 2 for the details about the energy consumption in Texel.

Texel's energy roadmap includes the plan of building 2 bio-digesters and also mentions that the ferry and fisher boats have their own sustainability projects [10]. So, this project will be focused on the transformation of electricity by renewables and mainly for private use.

3.2. Methodology

The project consists of three phases:

- I. Maximum PV panels installation with grid use as usual.
- II. Maximum PV panels and wind turbines installation with extra possible solutions on the grid use.
- III. Maximum PV panels and wind turbines installation with extra possible solutions on the grid and energy balancing options.

3.2.1. Phase I: Maximum PV

Electricity consumption is modeled in Homer to calculate the available grid capacity, based on that, and on the solar radiation, the maximum PV panels installation is calculated. The system will allow electricity exports to the mainland.

The energy balance will be completed with the system's information to calculate the total energy supply, CO₂ emissions, and energy neutrality level. Afterwards the cost-benefits analysis will be made, through a profit and loss statement, in order to calculate the overall cost per tonne of CO₂ emissions reduction. The tonnes of CO₂ emissions reduction are calculated by comparing the emissions from the base case.

3.2.2. Phase II: Maximum PV and wind turbines with extra solutions on the grid

The extra grid solutions will be added to the model to assess the extra RES capacity of the system and the same approach as phase I will be taken to calculate the total energy supply, CO₂ emissions, energy neutrality level, and cost tonne of CO₂ emissions reduction.

3.2.3. Phase III: Maximum PV and wind turbines with extra solutions on the grid and energy balancing options

Phase 2 would be taken as a base. The critical days will be identified, which the day where the imported and curtailed electricity are higher.

Based on the characteristics of this day the solutions for energy balancing would be defined, aiming to reduce electricity exports and imports to be able to increase the installation of PV panels and wind turbines. This might be an iterative process until the new energy management system is found. Matlab and Homer will be used for the calculations as shown in the following steps:

1. Get the data:
 - Original consumption load
 - RES production from Phase II
 - Maximum import and export capacity from Phase II

- Daily Natural Gas consumption for residential space heating and domestic hot water.
 - Daily fuel consumption for private transport
 - HP and EV profiles from actual field measurements
2. Calculate extra daily electricity load from heat pumps and electric vehicles based on actual NG and fuel consumption and HP and EV characteristics
 3. Calculate in Matlab the maximum capacity for HP and EV installation, combining the daily consumption and the (fixed) profiles and considering the limits of the critical days
 4. Simulate the Energy Management System in Matlab to balance the extra load from the HP and EV to obtain the new total consumption load
 5. Input the new total load in Homer and increase the PV panel and wind turbines installation to achieve the same level of electricity curtailment as in Phase II
 6. The expected results are:
 - Total load, and electricity purchased and sold to the grid (every 5-min)
 - New PV and wind turbines installation
 - Energy neutrality level
 7. As in the previous phases, the energy balance will be done to calculate the total energy supply, CO₂ emissions, and energy neutrality level; and the cost-benefits analysis will be done in order to calculate the overall cost per tonne of CO₂ emissions reduction.

Chapter 4. Phase I: Maximum implementation of PVs with a conventional grid, or business as usual

Texel's first approach was to achieve the energy neutrality goal by the implementation of PV panels. To get up to the 60% of the total goal, a PV installation of 350 MW is required [4]. Such an installation would have a big impact on the grid, will not only be very costly but would make the island more dependant of the mainland (see Figure 12).

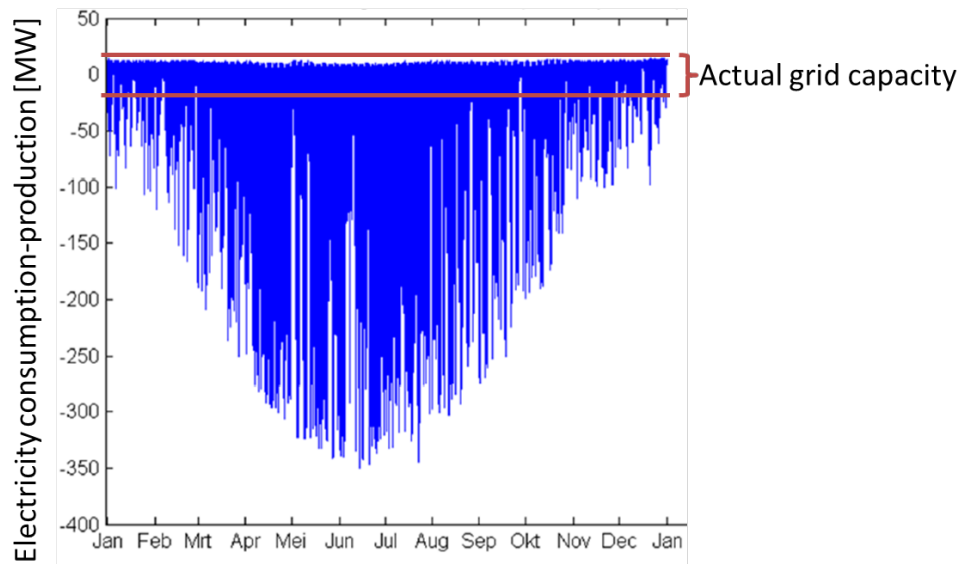


Figure 12. Net electricity, 1140 TJ produced by 350 MW PV panels installation [4]

The objective of this phase is to assess the maximum installation of PV panels in the island considering the actual electricity grid infrastructure. As mentioned on section 1.5, the bottleneck that is limiting the grid capacity is the transformer on the connection to the mainland with a capacity is of 18 MW. Analyzing in Homer the current electricity demand in a year, every 5 minutes and the maximum grid capacity the result was a maximum PV panels installation of 23 MW of power output. From the Homer model it was observed that in order to have a PV installation with such an output, a total install capacity of 27 MW is required.

The resulted energy balance of this scenario is presented in Table 4. The energy neutrality level achieved is of 5%, while the CO₂ emissions are reduced by 9% in comparison with the base case.

In comparison with the base Energy Balance (Table 2), imports have been reduced by 18% because some demand is fulfilled by the electricity from the PV panels, and from its total production 23% is exported due to the mismatch on supply and demand. A more graphic representation of the total energy consumption and production is shown in Figure 13 and Figure 14, and the cost-benefits analysis is included in Chapter 7.

Table 4. Phase I Energy Balance

| SUPPLY AND CONSUMPTION [TJ] | Elec. | Solar | Gas | Gasoline | Diesel | Total |
|--------------------------------------|------------|-----------|------------|------------|------------|-------------|
| Production | | 97 | | | | 97 |
| Imports | 198 | | 695 | 297 | 667 | 1857 |
| Exports | -22 | | | | | -22 |
| TOTAL ENERGY SUPPLY | 176 | 97 | 695 | 297 | 667 | 1933 |
| Distribution Losses | -7 | | | | | -7 |
| TOTAL FINAL CONSUMPTION | 265 | | 695 | 297 | 667 | 1924 |
| INDUSTRY SECTOR | 129 | | 258 | - | - | 387 |
| Other business use / unknown | 4 | | 6 | | | 9 |
| Services and trade | 55 | | 92 | | | 147 |
| Industry, logistics and construction | 12 | | 28 | | | 40 |
| Agriculture, Livestock and Fisheries | 11 | | 21 | | | 32 |
| Education, sport and government | 2 | | 7 | | | 9 |
| Hospitality and Tourism | 46 | | 105 | | | 151 |
| TRANSPORT SECTOR | | | | 297 | 667 | 964 |
| Road Private Transport | | | | 149 | | 149 |
| Road Business Transport | | | | 149 | | 149 |
| Ferry | | | | | 151 | 151 |
| Fishery | | | | | 515 | 515 |
| RESIDENTIAL SECTOR | 136 | | 437 | | | 573 |
| Private Houses | 103 | | 332 | | | 435 |
| Appliances | 103 | | | | | 103 |
| Space heating | | | 267 | | | 267 |
| Hot water | | | 56 | | | 56 |
| Cooking | | | 8 | | | 8 |
| Holiday Houses | 33 | | 106 | | | 139 |

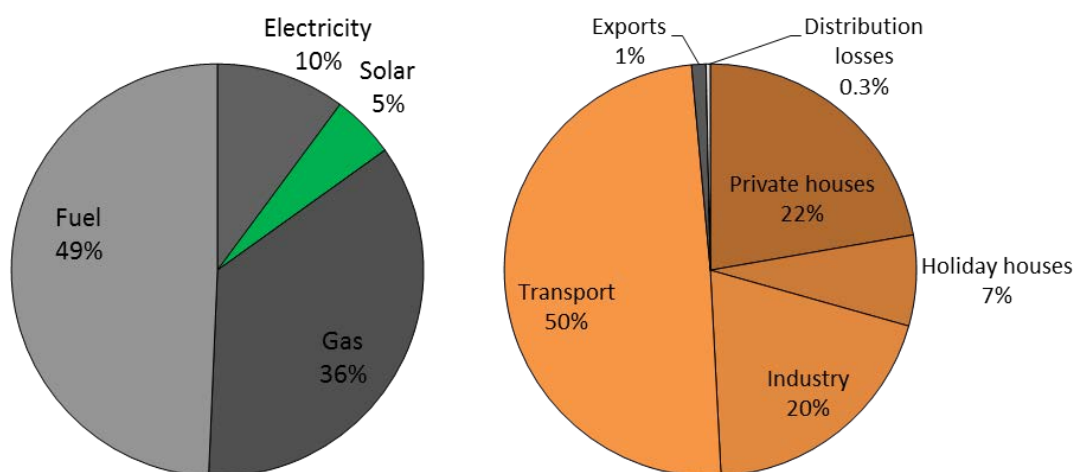


Figure 13. Electricity production and imports, and electricity consumption and exports from Phase I

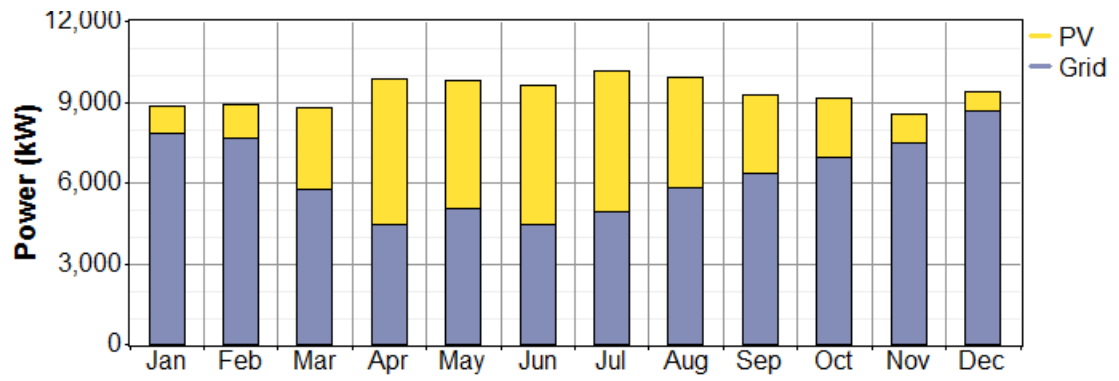


Figure 14. Monthly average electric production in phase I. Results from the model and data based on [11].

Chapter 5. Phase II: Improvements to the system by using the grid in a more optimal and smarter way with no large extra investment

From Phase I it is observed that the goal cannot be achieved with only PV panels without increasing the capacity of the grid and thus the dependability with the mainland. New solutions have to be proposed on the use of the grid and on the energy sources. This phase evaluates the possibility to increase the renewable energy conversion on-site by implementing smart solutions to optimize the use of the current electricity grid infrastructure to avoid high investment costs.

The options analyzed in this phase are listed below. Some of the ideas might sound simple but are already different from the “business as usual” and might represent some changes on the current requirements [11].

5.1. Use of the backup infrastructure and addition of an extra transformer.

As has been explained, the transformer is the bottleneck in this case. Adding an extra transformer does not represent a big change or investment, and increases the total grid capacity.

The backup infrastructure is required for electricity security. The backup cable and transformer are only used in emergencies to assure that electricity is delivered at all times. Since the extra capacity is needed for electricity exports and not for fulfilling the electricity demand, the backup infrastructure could be used when available. This measure already increases the grid’s export capacity from 18 MW to 33 MW (limited by the island available grid capacity). It is important to note that the grid’s import capacity remained in 18 MW.

5.2. Introducing wind energy to take advantage of the compatibility of wind and solar energy availability.

Diversifying the energy sources gives the opportunity to use and export renewable electricity in different times and thus to reduce the total purchase of electricity and increasing the level of energy neutrality.

5.3. Cable pooling.

Nowadays it is required to install full grid capacity for each installation. If it is consider the real use of the grid by the PV and wind turbines installations, a new way of using the grid could be introduced, where as in car-pooling the infrastructure is shared among the two technologies avoiding the need of the installation of extra grid capacity.

The compatibility of these two technologies was analyzed in Alliander by Bastian Knoors and the results show that, in The Netherlands, the same grid infrastructure could be used for an equivalent installation of PV and wind turbines and will be enough to fulfill the requirements of both installations 97% of the time [17]. The results are presented in Figure 15. The input for this analysis was:

- PV and wind turbine installations of 9 MW power peak each
- Power curve of a 2 MW wind turbine (Enercon 82E), with approximately 2000 full-operation hours per year

- Solar panels (linear production from 0 to 1000 watt/m²) with 30 degrees horizontal tilt and directed to the south
- Inverter efficiency of 97%
- 10 years of 10 minute interval solar and wind speed data form Cabauw (The Netherlands)

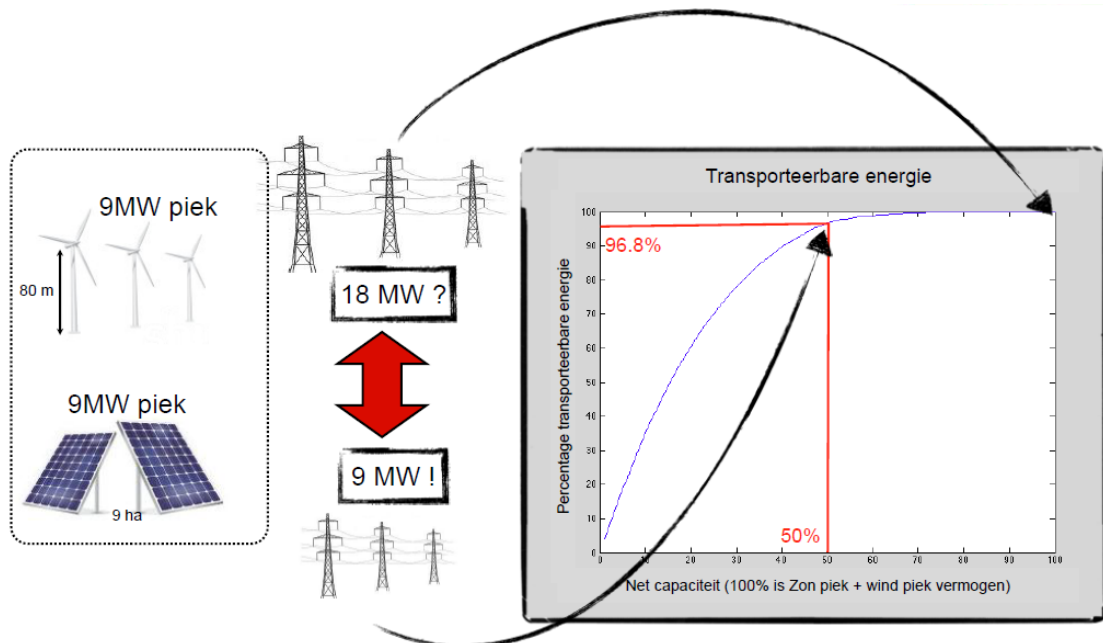


Figure 15. "Gelijktijdigheid is sleutel tot goedkoper transport" study results showing the feasibility of cable-pooling on PVs and wind turbines installations in The Netherlands [17]

5.4. Electricity curtailment.

As can be observed in the load duration curve of solar and wind power showed in Figure 16, there are only a few moments where its full capacity is achieved. Disabling electricity production on these cases would not represent a big loss on electricity but could 'free' some grid capacity, so the RES installations could be increased. In this study, the terms excess electricity and electricity curtailment are used indistinctively.

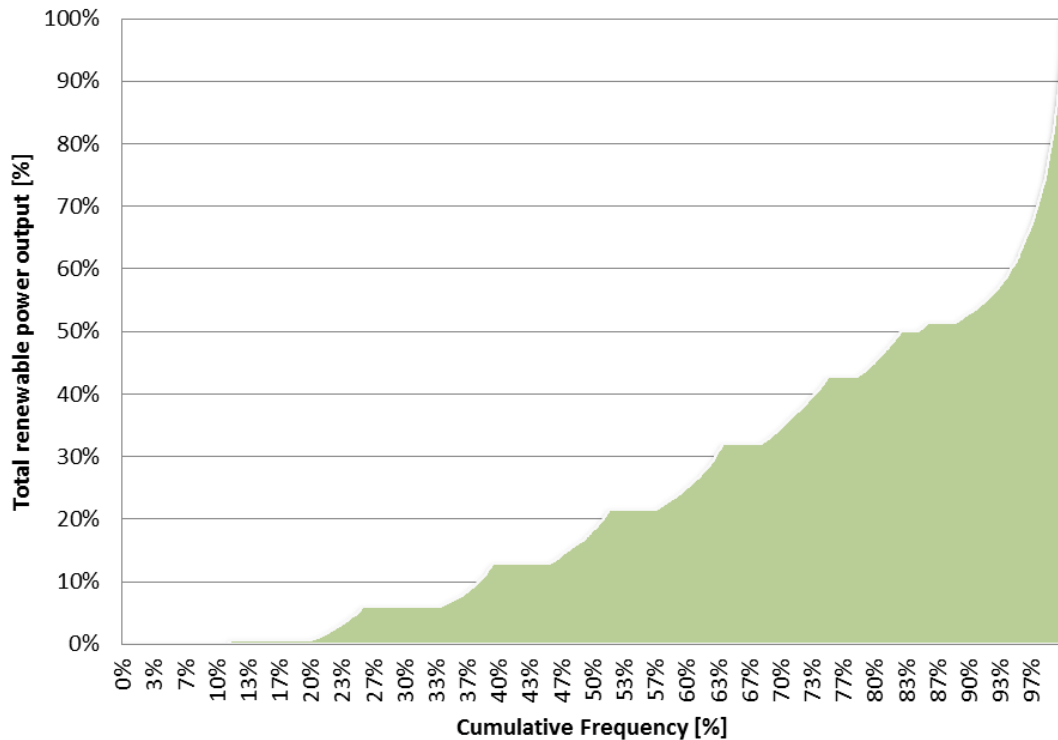


Figure 16. Load duration curve of solar and wind power from Phase II.

The resulted PV panels and wind turbine installations with a power peak of 48 MW each. In the model to achieve this maximum peak on both technologies the total capacity installation of PV is of 56 MW and of wind turbines of 48 MW. A 32% of energy neutrality is achieved and 54% of the CO₂ emissions are avoided. As in the energy balance for Phase I, not any changes on the final consumption were made. In this phase, 34% of the total energy is produced by renewables. This electricity would be enough to supply 100% of the electricity demand if it was required when the RES are available, due to this mismatch 60% of the electricity produced has to be exported and the island still has to import 25% of its total electricity demand. Some graphic representation of the total energy consumption and production are shown in Figure 17 and Figure 18 and the new energy balance is shown in Table 5.

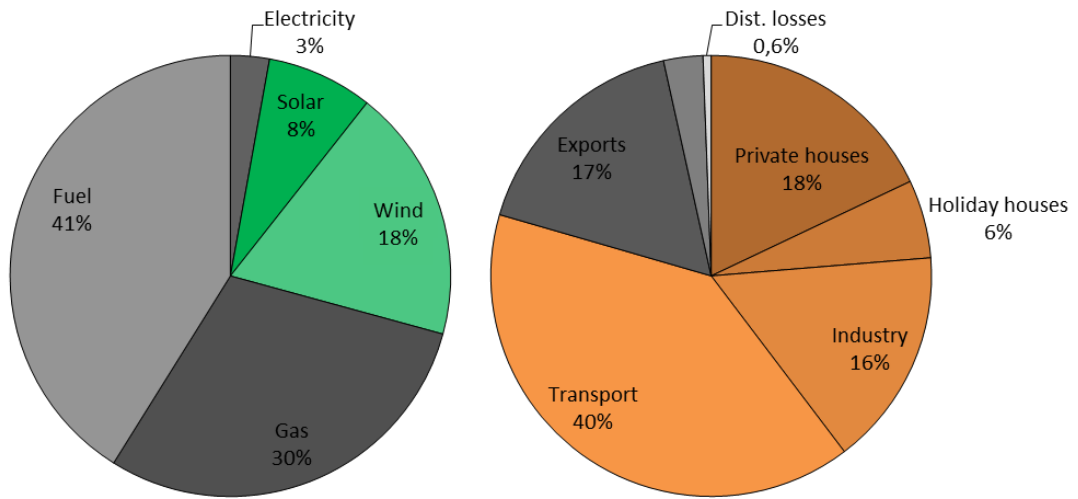


Figure 17. Phase II, Electricity production and imports, and electricity consumption and exports

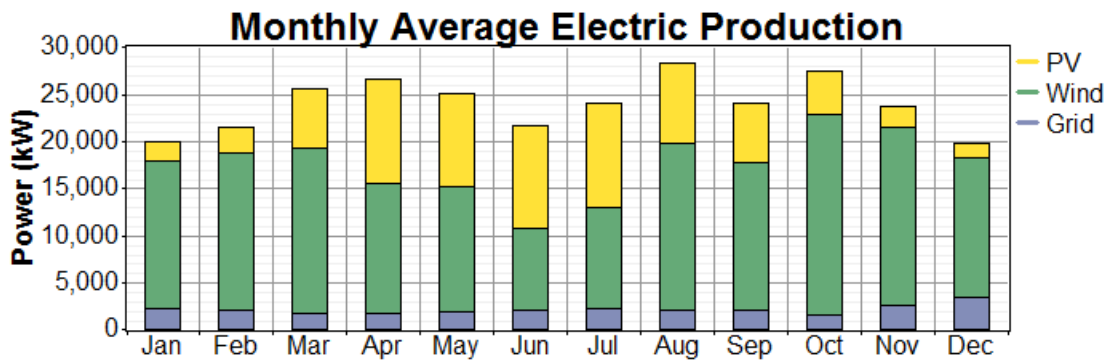


Figure 18. Monthly average electric production from PV panels and wind turbines and imported from the grid in Phase II. Data based on [11].

Table 5. Phase II Energy Balance

| SUPPLY AND CONSUMPTION [TJ] | Elec. | Solar | Wind | Gas | Gasoline | Diesel | Total |
|--------------------------------------|--------------|--------------|-------------|------------|-----------------|---------------|--------------|
| Production | | 203 | 486 | | | | 689 |
| Imports | 67 | | | 695 | 297 | 667 | 1726 |
| Exports | -412 | | | | | | -412 |
| TOTAL ENERGY SUPPLY | -346 | 203 | 486 | 695 | 297 | 667 | 2002 |
| Excess electricity | -70 | | | | | | -70 |
| Distribution Losses | -14 | | | | | | -14 |
| TOTAL FINAL CONSUMPTION | -541 | 237 | 570 | 695 | 297 | 667 | 1924 |
| INDUSTRY SECTOR | 129 | | | 258 | - | - | 387 |
| Other business use / unknown | 4 | | | 6 | | | 9 |
| Services and trade | 55 | | | 92 | | | 147 |
| Industry, logistics and construction | 12 | | | 28 | | | 40 |
| Agriculture, Livestock and Fisheries | 11 | | | 21 | | | 32 |
| Education, sport and government | 2 | | | 7 | | | 9 |
| Hospitality and Tourism | 46 | | | 105 | | | 151 |
| TRANSPORT SECTOR | | | | | 297 | 667 | 964 |
| Road Private Transport | | | | | 149 | | 149 |
| Road Business Transport | | | | | 149 | | 149 |
| Ferry | | | | | | 151 | 151 |
| Fishery | | | | | | 515 | 515 |
| RESIDENTIAL SECTOR | 136 | | | 437 | | | 573 |
| Private Houses | 103 | | | 332 | | | 435 |
| Appliances | 103 | | | | | | 103 |
| Space heating | | | | 267 | | | 267 |
| Hot water | | | | 56 | | | 56 |
| Cooking | | | | 8 | | | 8 |
| Holiday Houses | 33 | | | 106 | | | 139 |

Chapter 6. Phase III: Maximum installation of PVs and wind turbines with extra solutions on the grid and energy balancing options

Phase III focuses on using as much as the energy produced on Phase II as possible. The aim is to see how much could energy balancing through an energy management system help to achieve the goal of electricity neutrality. Besides the energy management options, other technologies that facilitate the balancing will be added to the system. Because electricity production is already larger than the total electricity consumption, this demand will be increased by electrifying part of the heating and transport demand. Since space heating and domestic hot water represent the major consumption of gas, individual heat pumps for the private houses will be included. Also, the introduction of electrical vehicles for private transport will be analyzed. Private transport is not the largest part of transport demand but, as mentioned on Texel's Energy Roadmap, the ferry and fishing boats can be handled separately because they have their own sustainability plans [10].

The critical days for the calculations are the day of highest imported and curtailed electricity. Based on the characteristics of these days the maximum capacity of heat pumps and electrical vehicles will be calculated. The aim is to reduce electricity exports and imports to be able to increase the installation of PV panels and wind turbines. Daily heating and transport demand will be considered for the calculations, assuming a daily storage buffer for both solutions for simplification. This might be an iterative process until the new energy management system is found. Matlab will be used for the calculations.

6.1. Heat pumps

From the gas consumed in the private houses in 2009, 80% was used for heating, 17% for hot water and 2% for cooking [12]. This results on a total consumption of 323 TJ of gas consumption for heating and hot water.

Heat pumps are an efficient way to fulfill these needs, giving the opportunity to reduce the energy consumption and to shift some electricity demand to when the RES are available. The heat pumps take energy from a heat source and give it away on a heat sink. The heating cycle is shown in Figure 19. Because part of the heating is taken from the heat source, most of the electricity used is the electricity required by the compressor, making the heat pump very efficient. The coefficient of performance of this type of equipment depends on the heat output required ($COP=Q_{out}/W_{e,in}$). Based on the temperature information considering the maximum heating demand throughout the year, the domestic hot water demand and the total number of private houses, it was decided that an air to water heat pump of 8 kW would be enough to supply the heating demand. An air to water heat pump was chosen because it would be easier to fit in the short term into existing buildings because of its characteristics. The information of the heat pump given by the supplier is included in Appendix II. The calculations for space heating and hot domestic water are done separately since they depend on different factors.

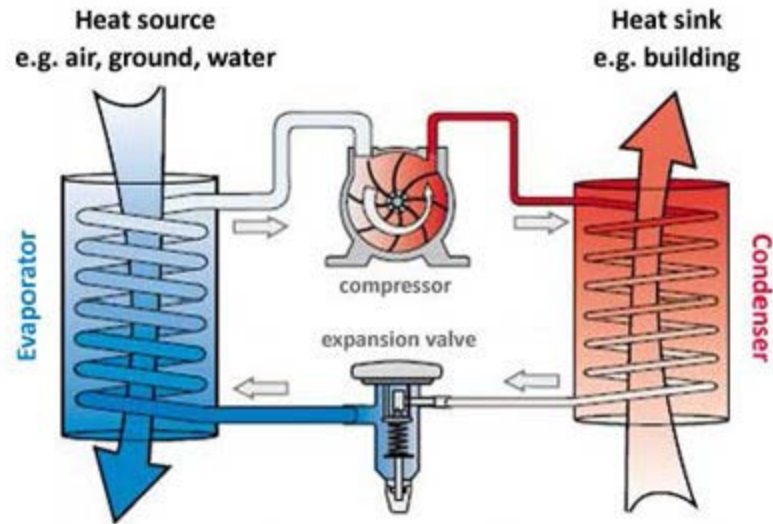


Figure 19. Heat pump cycle [18]

6.1.1. Space heating

Considering the hourly temperatures of that same year [15], the total annual Heating Degree Days (HDD) of Texel are 2743, using 18 °C as base temperature appropriate for the inside of the house. The Cooling Degree Days (CDD) are minimal, only 54 in total, so cooling is not included in the analysis. The monthly HDD and CDD can be seen in Figure 20.

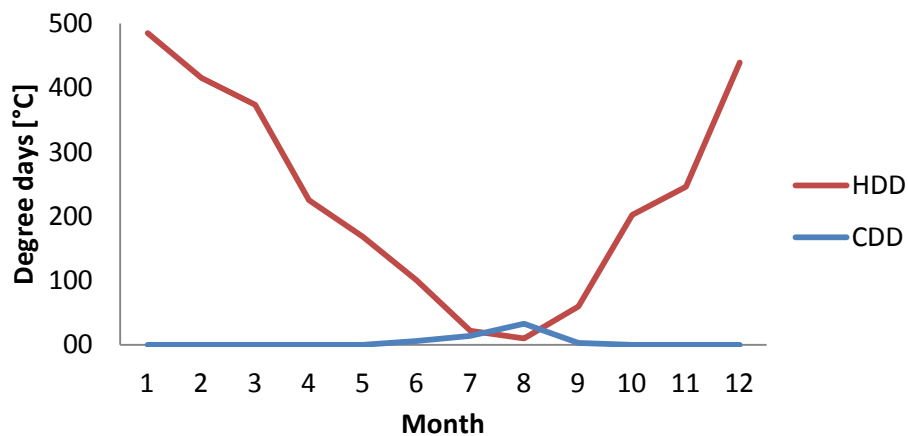


Figure 20. Heating and Cooling Degree Days of Texel based on [15].

The electricity required for each heat pump was calculated on a daily base, assuming that a hot water tank is available to store the total hot water needed during the day. The calculations are based on the temperature difference of the average daily temperature and the inside temperature of 18 °C. The COP also depends on this difference and the value used on each day was the closest match to the supplier information. The energy demand of a single household for space heating changed from 55 GJ of natural gas per year to 17 GJ of electricity.

6.1.2. Domestic hot water

The daily consumption of hot water was considered the same for every household throughout the year. The COP is smaller than for space heating since the water should be heated up to 55°C. The approach is on a daily basis as with the space heating. Heat pumps and electric vehicles profiles

The heat pumps and electric vehicles profiles were taken from actual measurements from water-to-water heat pumps installed in-line houses and electric vehicles charging stations in The Netherlands. Measurements with exact same conditions as the study case are not available but these can be taken as representative since the use is the same.

Different profiles for weekdays and weekends are defined, these profiles are shown in Figure 21 to Figure 24.

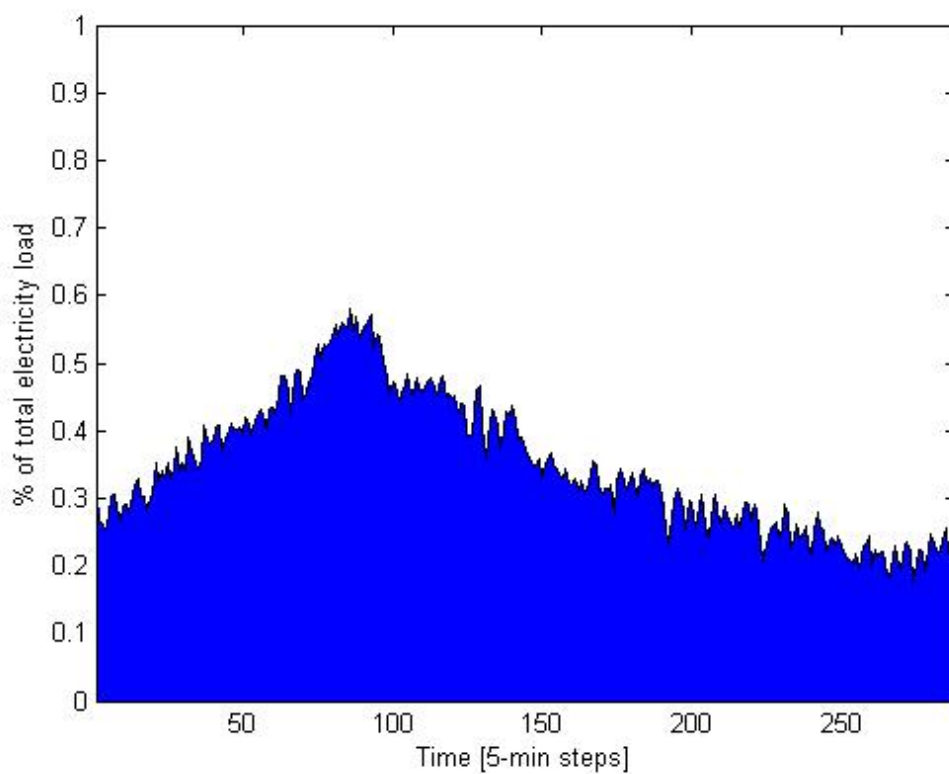


Figure 21. Heat pump weekdays profile.

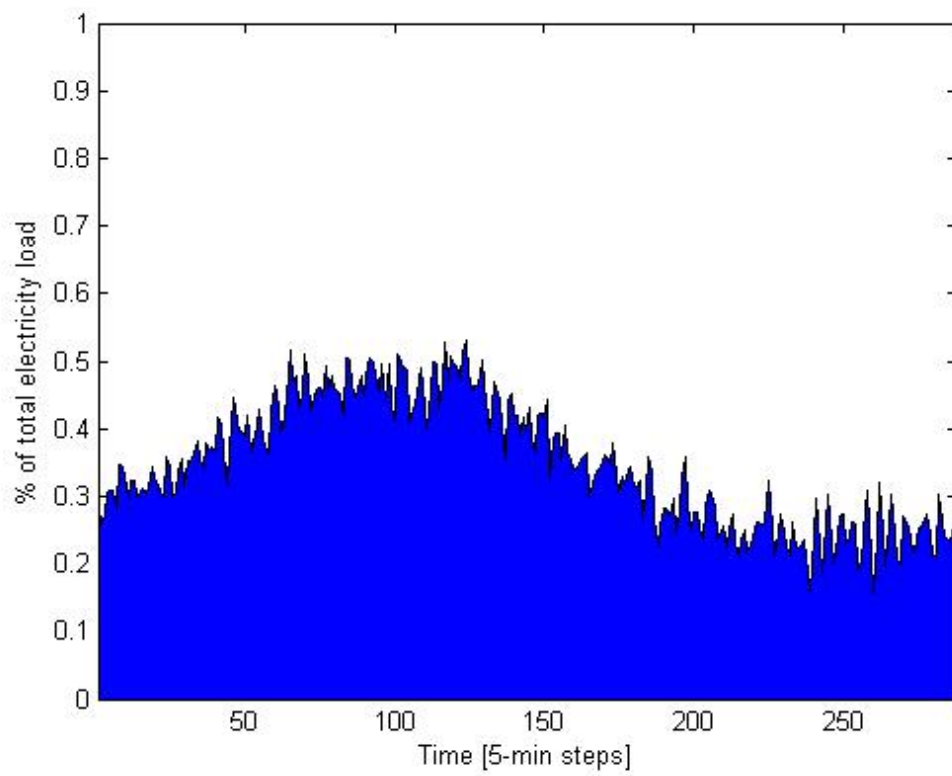


Figure 22. Heat pump weekend profile

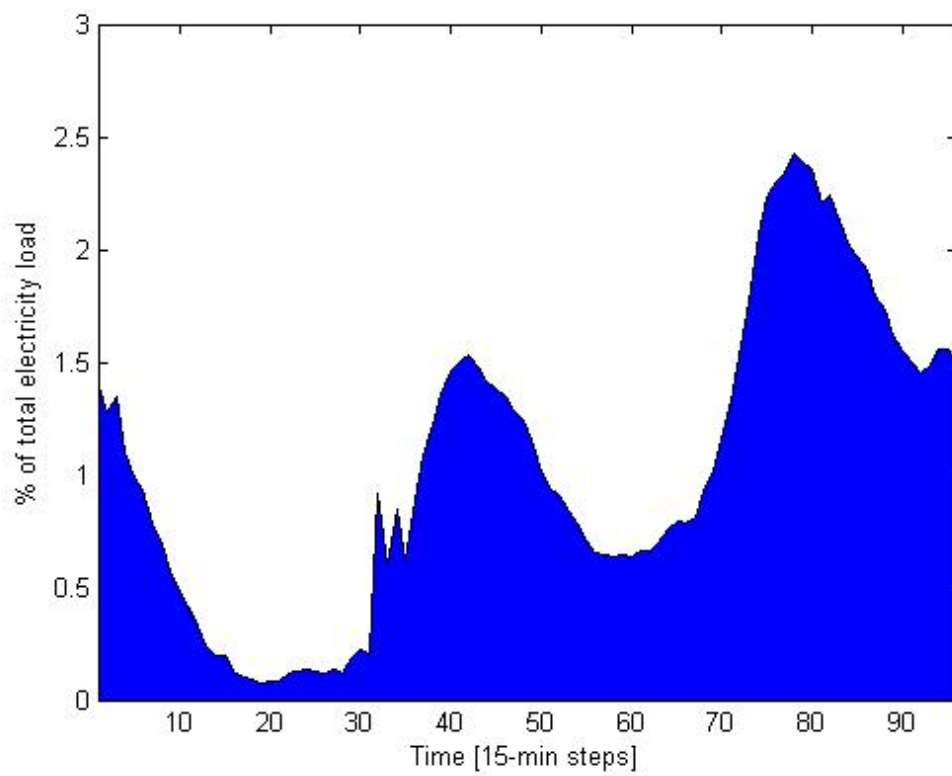


Figure 23. Electric vehicles weekdays profile

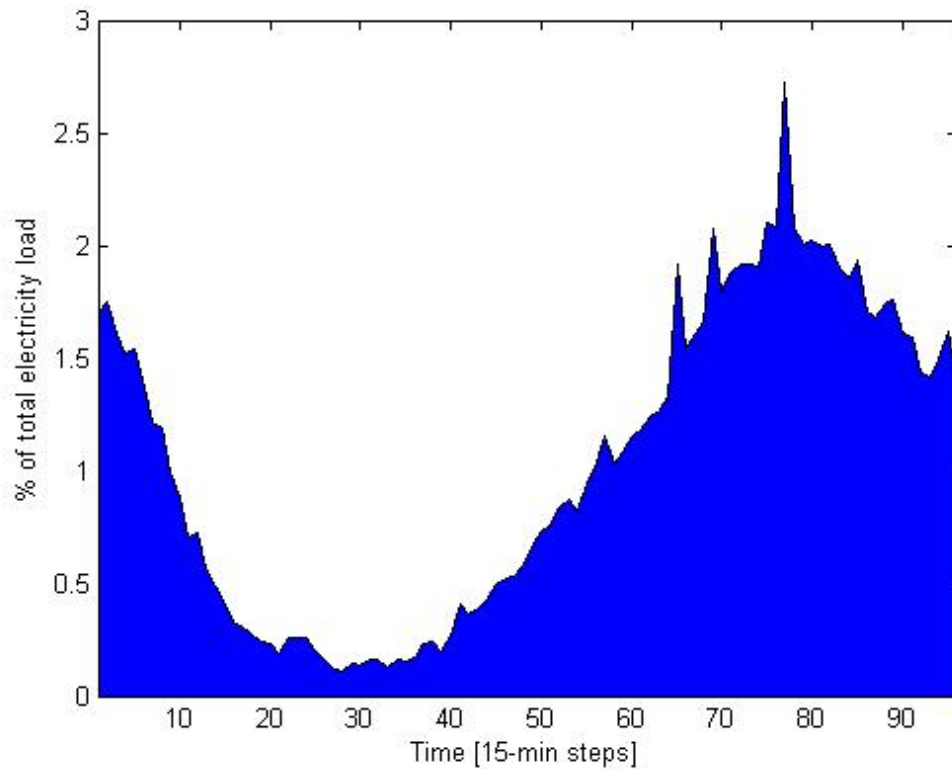


Figure 24. Electric vehicles weekend profile

6.2. Electrical vehicles

For simplicity the daily use of private cars is considered the same along the year, resulting in a total consumption of 410 GJ of fuel per day. Considering the typical overall efficiency of Otto-engines of 20% [16] [19] and the approximate efficiency of an electrical vehicle of 63% [19] the total daily electricity demand for private transport is of 130 GJ. The breakdown per main components of both types of vehicles is shown in Figure 25 and Figure 26.

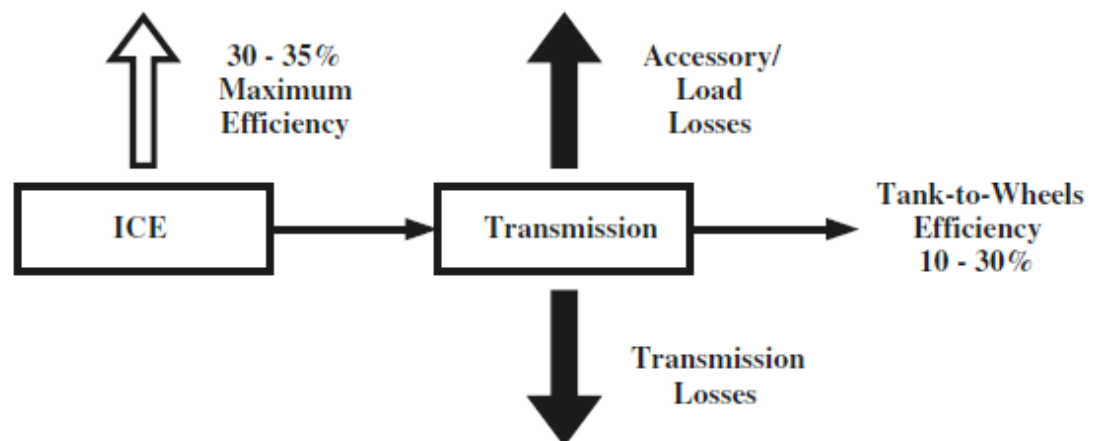


Figure 25. Theoretical tank-to-wheel efficiency of a typical gasoline engine vehicle [19].

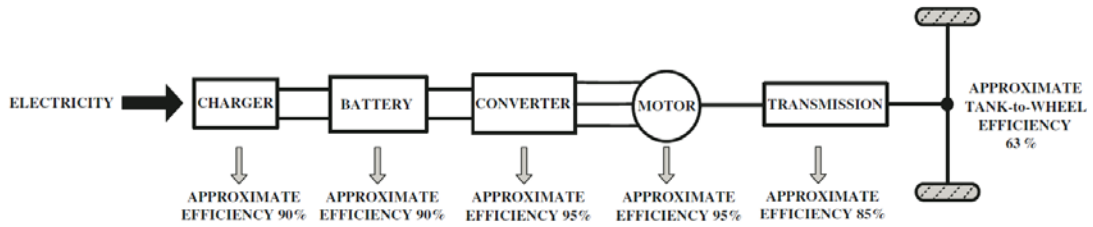


Fig. 2.1 Approximate calculation of theoretical drive train efficiency for EV, based on power component stage analysis

Figure 26. Approximate tank-to-wheel efficiency of an EV [19].

6.3. Energy Management System (EMS)

For this study it is assumed that the EMS is capable of perfectly balancing the new extra electricity demand with the current electricity production and use. That is, it will allocate the extra electricity on each day, from the highest peak of the excess electricity graph down, and then continue in the same way with the exports, if this available electricity is not enough to fulfill the extra requirements the rest of the electricity will be imported, starting on the time when the imports are lower. The simulation of this balancing is done in Matlab with values obtained from the Homer model every 5 minutes. A simplified flow diagram of the Matlab model is shown below. A more detailed flow diagram is on Appendix III.

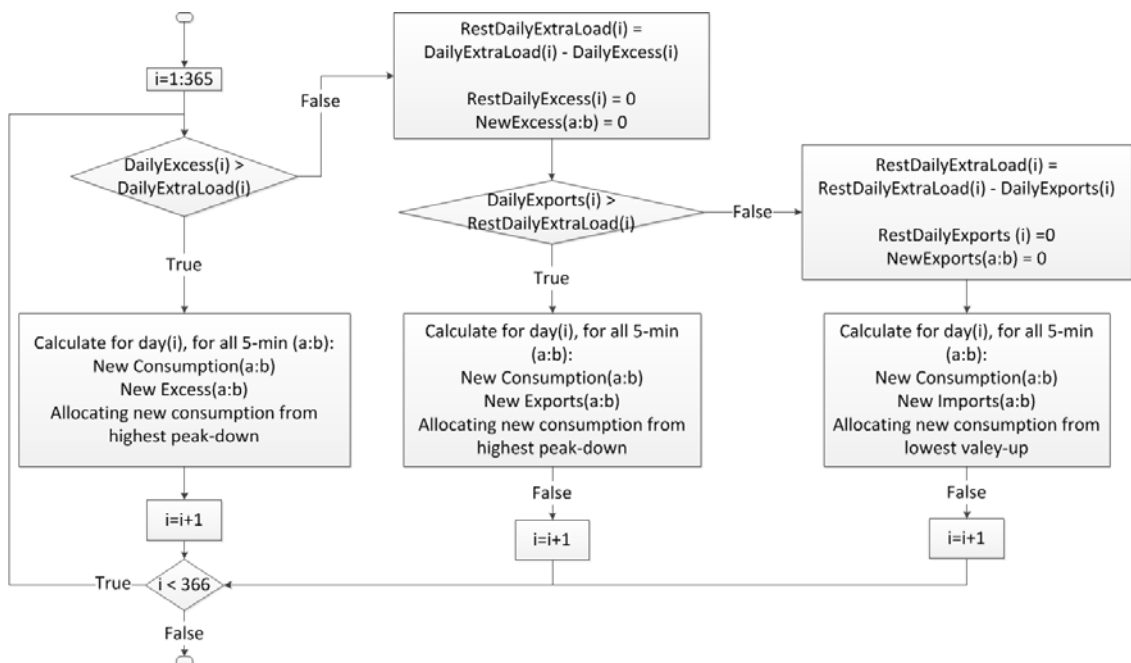


Figure 27. Simplified flow diagram for the Matlab model simulating the EMS.

A 100% installation of heat pumps and electric vehicles, with fully balanced energy, would result in a reduction of excess or curtailed electricity and electricity exports, and in this case an increase of electricity imports, as shown in Table 6. This table also shows a 0.1 TJ of unmet electricity, which is because in one day of that year the load exceeds the maximum import capacity.

Table 6. Grid impact of 100% heat pumps, electrical vehicles and EMS

| | Base case (Phase II results) | Case: 100% HP, EV, EMS |
|--|------------------------------|------------------------|
| Electricity Imports [TJ] | 67 | 88 |
| Electricity Exports [TJ] | 479 | 402 |
| Excess Electricity [TJ] (curtailed electricity) | 108 | 44 |
| Unmet Electricity [TJ] | 0 | 0.1 |

To zoom in into the grid impact, 2 critical days are chosen. The first day is when the renewable energy is scarce and the demand is high, resulting in the highest electricity import; the second is the opposite, resulting in the highest amount of curtailed electricity, or excess electricity that in phase II falls into the 10% electricity curtailment. The 5-min behavior during these days is shown below. In the first case, we can see the day where the load is higher than the import capacity by 2 MW along the whole day; and in the second case we can see how electricity excess decrease the original peak, resulting in an overall peak reduction of 18% in this specific day.

6.3.1. Critical day 1: High Imports

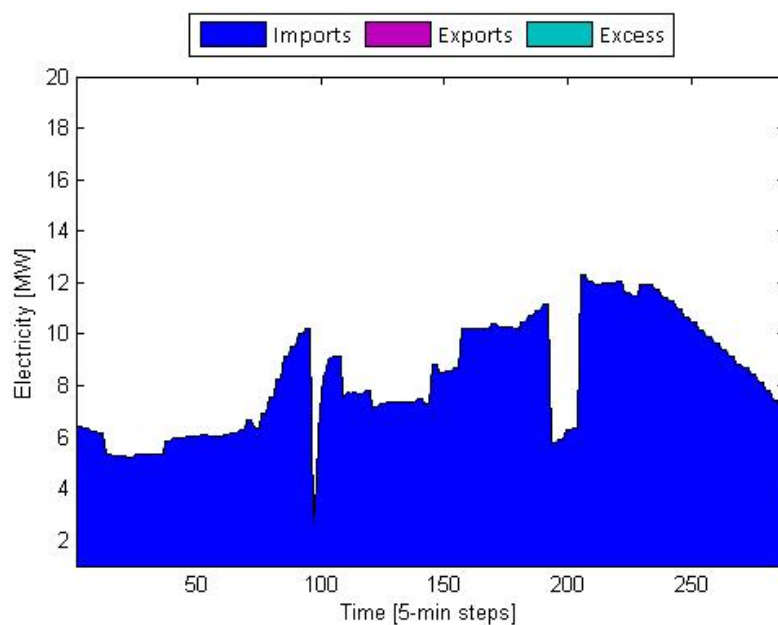


Figure 28. Grid use on critical day 1, Base case (Phase II results)

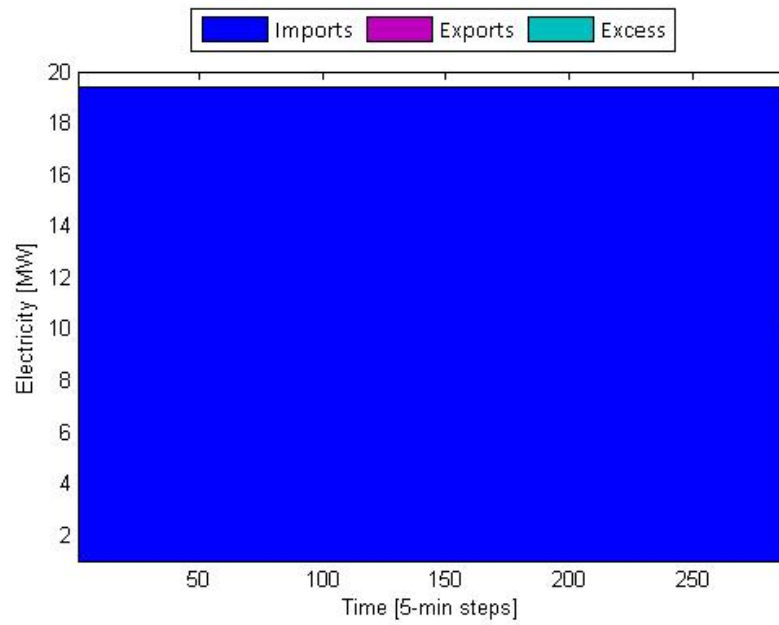


Figure 29. Grid use on critical day 1, Case: 100% HP, EV, EMS

6.3.2. Critical day 2: High Excess (high curtailment)

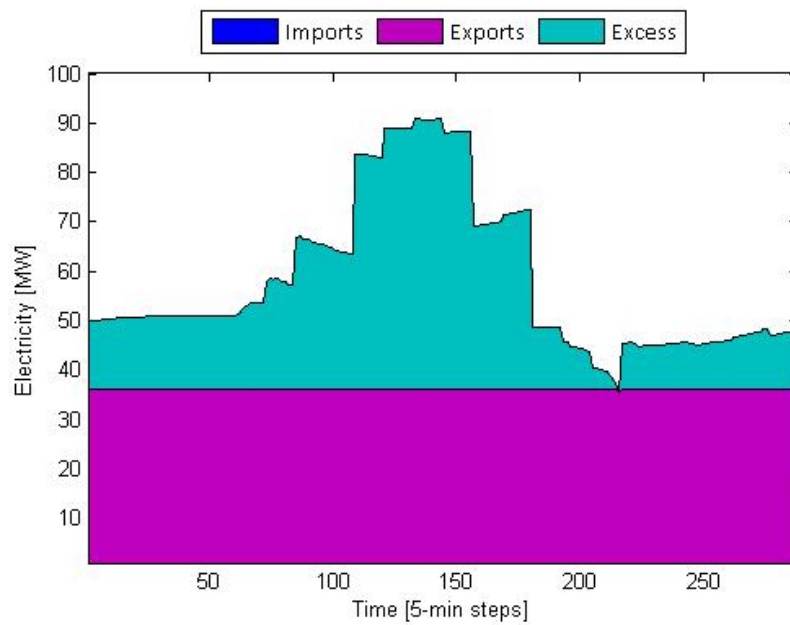


Figure 30. Grid use on critical day 2, Base case (Phase II results)

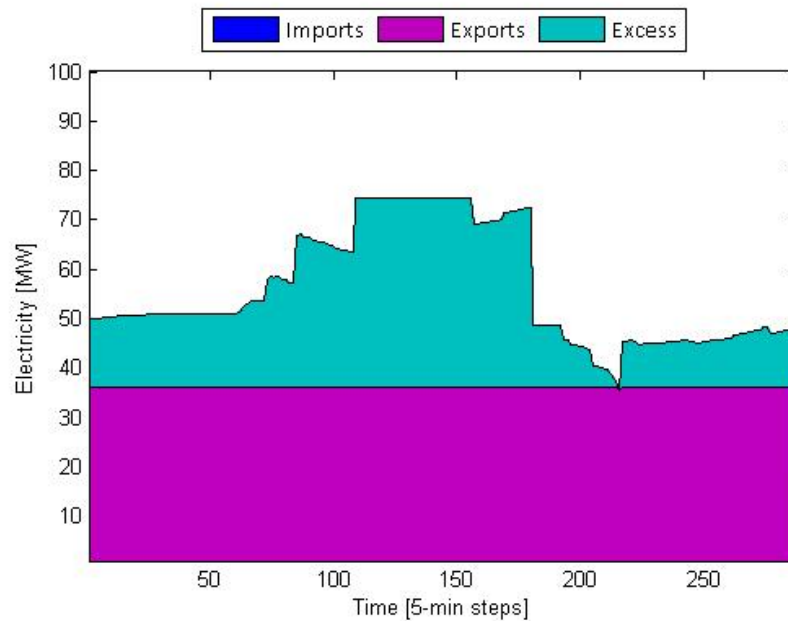


Figure 31. Grid use on critical day 2, Case: 100% HP, EV, EMS

6.4. Maximum capacity of heat pumps and electrical vehicles

As showed in Figure 29, the grid cannot handle the extra load of the total extra load of the heat pumps and electrical vehicles, not even if the EMS balances 100% of this extra load. To calculate the maximum amount of heat pumps and electrical vehicles that could be installed in the island the worst case is assumed. This case is when all HP and EV are functioning according to the average observed daily curve. These power curves are shown in Figure 21 to Figure 24.

The extra daily electricity load fulfilling the residential space heating and domestic hot water requirements, and the private transport was modeled to be supplied following the weekdays and weekends profiles. Having as a base the Phase II, and setting the limit of maximum import capacity of the grid as 18 MW, the extra load was modeled in Matlab to calculate the maximum installation of HP and EV that the grid can handle. The flow diagram of the Matlab model and the code are included in Appendix III.

The resulted maximum HP and EV installation is 41.25% of the total, so an estimated total of 2496 HP and 2342 personal EV.

6.5. Maximum capacity of PV panels and wind turbines installations

The daily extra load from a single HP and EV is multiplied by the maximum installed capacity for each technology. This new daily load is run in the Matlab simulation of the EMS to balance the new extra load with the available electricity from the Phase II, to finally obtain the new total load. This load is then input in Homer where the PV panels and wind turbines installations are increased until the level of electricity curtailment is 10%, as in

Phase II. The new maximum capacity of renewables is of 64 MW of PV panels and 54 MW for wind turbines. Both installations will result in a maximum peak power of 54 MW. The new energy flow values are presented in Figure 32 and Table 7. Note that even if the percentages from Figure 32 did not change much compared with Phase II, the total energy consumption changed from 1.9 TJ to 1.8 TJ and the energy supply from 2 TJ to 1.96 TJ. The new level of energy neutrality is 46%.

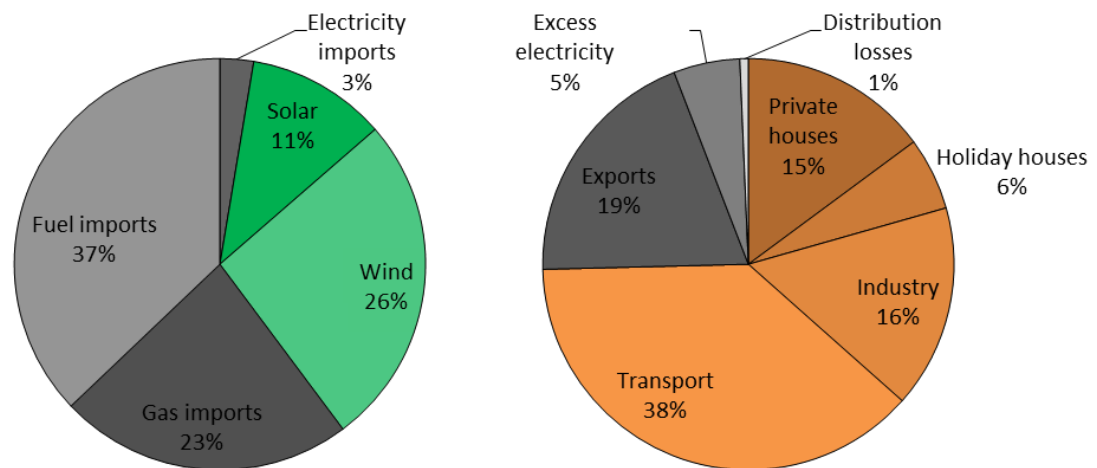


Figure 32. Phase III, Electricity production and imports, and electricity consumption and exports

Table 7. Phase III Energy Balance

| SUPPLY AND CONSUMPTION [TJ] | Elec. | Solar | Wind | Gas | Gasoline | Diesel | Total |
|--------------------------------------|--------------|--------------|-------------|------------|-----------------|---------------|--------------|
| Production | | 229 | 553 | | | | 782 |
| Imports | 69 | | | 562 | 236 | 667 | 1534 |
| Exports | -423 | | | | | | -423 |
| TOTAL ENERGY SUPPLY | -355 | 229 | 553 | 562 | 236 | 667 | 1893 |
| Excess electricity | -82 | | | | | | -82 |
| Distribution Losses | -15 | | | | | | -15 |
| TOTAL FINAL CONSUMPTION | 353 | | | 559 | 235 | 667 | 1796 |
| INDUSTRY SECTOR | 129 | | | 258 | - | - | 387 |
| Other business use / unknown | 4 | | | 6 | | | 9 |
| Services and trade | 55 | | | 92 | | | 147 |
| Industry, logistics and construction | 12 | | | 28 | | | 40 |
| Agriculture, Livestock and Fisheries | 11 | | | 21 | | | 32 |
| Education, sport and government | 2 | | | 7 | | | 9 |
| Hospitality and Tourism | 46 | | | 105 | | | 151 |
| TRANSPORT SECTOR | 19 | | | | 236 | 667 | 922 |
| Road Private Transport | 19 | | | | 88 | | 107 |
| Road Business Transport | | | | | 149 | | 149 |
| Ferry | | | | | | 151 | 151 |
| Fishery | | | | | | 515 | 515 |
| RESIDENTIAL SECTOR | 195 | | | 305 | | | 498 |
| Private Houses | 161 | | | 199 | | | 360 |
| Appliances | 103 | | | | | | 103 |
| Space heating | 48 | | | 157 | | | 205 |
| Hot water | 10 | | | 33 | | | 43 |
| Cooking | | | | 8 | | | 8 |
| Holiday Houses | 33 | | | 106 | | | 139 |

Chapter 7. Cost-benefit analysis from the social perspective

The solutions can be analyzed from different perspectives depending on the aim of the analysis; in this case the societal benefit from the whole energy system is to be assessed in terms of cost per CO₂ emissions reduction. The time period for the projection is 40 years, since is the average time life of the grid installation. Based on the three phases described before, the following scenarios were created:

0. Base scenario. Based on Texel's 2009 Energy Balance [10] [12]. No extra technologies were included.
1. Improvements to the system by using the grid in a more optimal and smarter way with no large extra investment.
2. Maximum installation of PVs and wind turbines with extra solutions on the grid and energy balancing options.
3. Maximum installation of PVs and wind turbines with extra solutions on the grid and energy balancing options (heat pumps, electrical vehicles, and an energy management system).

The main characteristics of all scenarios are listed in the following table. These characteristics are based on the results from the project phases.

Table 8. Characteristics of case scenarios

| | Units | 0 | 1 | 2 | 3 |
|--|-------------------------|-----|-----|-----|-----|
| Energy neutrality | % | 0 | 5 | 32 | 38 |
| Reduction of CO ₂ emissions | kt/year | - | 12 | 78 | 91 |
| Electricity Imports | TJ | 274 | 98 | 67 | 69 |
| Electricity Exports | TJ | 0 | 22 | 412 | 423 |
| Gas consumption households | TJ | 332 | 332 | 332 | 199 |
| Gas consumption commercial | TJ | 364 | 364 | 364 | 364 |
| Gasoline consumption | TJ | 297 | 297 | 297 | 236 |
| Diesel consumption | TJ | 667 | 667 | 667 | 667 |
| PV installation | MWp | - | 23 | 48 | 54 |
| Wind turbines installation | MWp | - | - | 48 | 54 |
| Heat pumps installation | % of total households | - | - | - | 41% |
| Electric vehicle installation | % of total private cars | - | - | - | 41% |

For the calculations average data from existing technologies was used. These parameters are shown in Table 9 and are based on the "Casus Texel" by D-Cision and on information of previous projects of the company. Notice that no subsidy was taken into account to avoid externalities that would affect the results.

Table 9. Technology data

| | | PV panels | Wind turbines | Heat pumps | Electric vehicles | Energy management system | Hot water tank |
|--|------------------------------|-----------|---------------|----------------|-------------------|--------------------------|----------------|
| Investment cost of installation ¹ | M€/MWp | 1,53 | 1,20 | - | - | - | - |
| | €/unit | - | - | 2800 | 15000 | 1412 ² | 1500 |
| Price reduction per year | % of installation investment | 5 | 1 | 2 | 2 | 2 | 2 |
| Operation and maintenance costs | % of installation investment | 2 | 5 | 2 ³ | 0 ^{3,4} | 10 ⁵ | 2 |
| Lifetime | Years | 20 | 15 | 15 | 10 | 10 | 10 |

1. The investment cost of installation includes all extra equipment needed and costs related.
2. The cost of the EMS is based on actual costs of the Cloud Power Project [20].
3. The electricity required to operate the heat pumps and electric vehicles is not included in this percentage but on the energy balance.
4. The maintenance of the electric vehicle is set to 0 because there is not a considerable difference between the maintenance of a fuel injection car, and only the differences with the base scenario are considered.
5. O&M for the EMS includes the entire infrastructure behind the system.

7.1. Difference analysis Capex (Capital Expenses)

The costs and profits are calculated in relation of the base scenario. In the base scenario there are no Capex, for the rest of the scenarios the Capex include the initial investment of the technologies suggested. The installation is supposed to happen along 5 years, and the re-investment of the replacement of the equipment after its life time is included for the total time period (40 years). The price at start is the one stated on the table and this is reducing as indicated. The yearly Capex for the 3 scenarios are included in the profit and loss statements on the excel sheet attached.

7.2. Difference analysis OPEX (Operating Expenses)

The OPEX are composed by three parameters:

- a. The savings on energy costs by the decrease of energy imports.
- b. The profits from the electricity exports.
- c. The maintenance of the technologies installed.

The energy consumption is considered to be constant along the 40 years [1]. The energy prices used are based on the rates of Texel Energie, before taxes and other charges. The extra charges are not included to avoid uncertainty along the long period studied and to produce objective results that are not affected by externalities. In the case of electricity, the same price is considered for all users, and for selling and buying; as the net electricity cost is calculated in a yearly base (“saldering”).

Table 10. Energy prices

| | Units | Price |
|-------------|------------------|-------|
| Electricity | €/kWh | 0.06 |
| Gas | €/m ³ | 0.34 |
| Gasoline | €/lt | 0.72 |
| Diesel | €/lt | 0.75 |

The profit from the electricity production and the maintenance costs are calculated based on the amount of technology installed every year. Since the initial installation is done during the first 5 years, on those years the profits are calculated based on the total production of the full solution and the percentage of equipment installed. Further analysis has to be done to include the decrease of efficiency along the lifetime of each the equipment. The maintenance costs also vary together with the actual installations per year. The yearly OPEX for the 3 scenarios are included in the profit and loss statements on the excel sheet attached.

The cash flow and discounted cash flow (with the discount rate of 4%), including the Capex and OPEX and showed in the next figures. It can be noticed on the graphs that the investment is not recovered in the period considered.

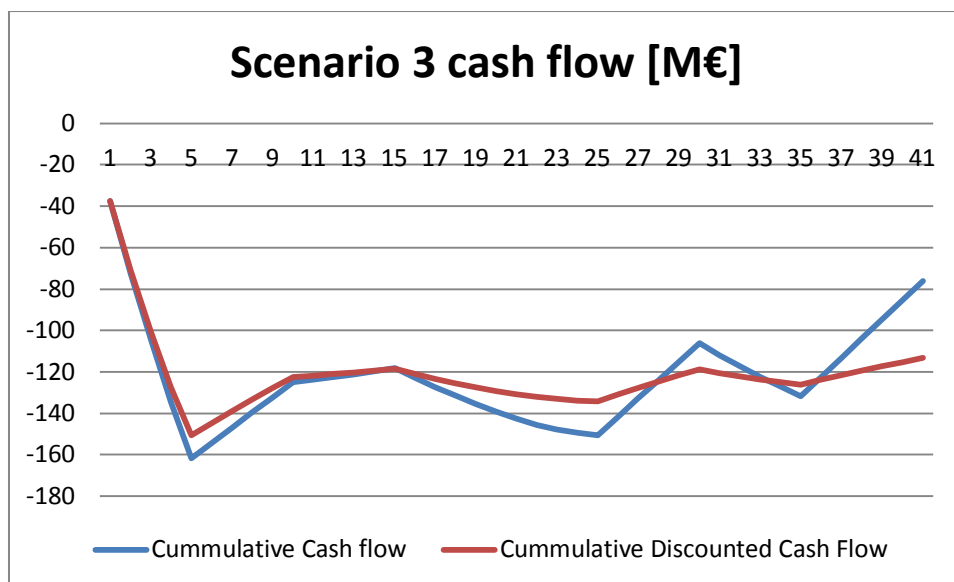
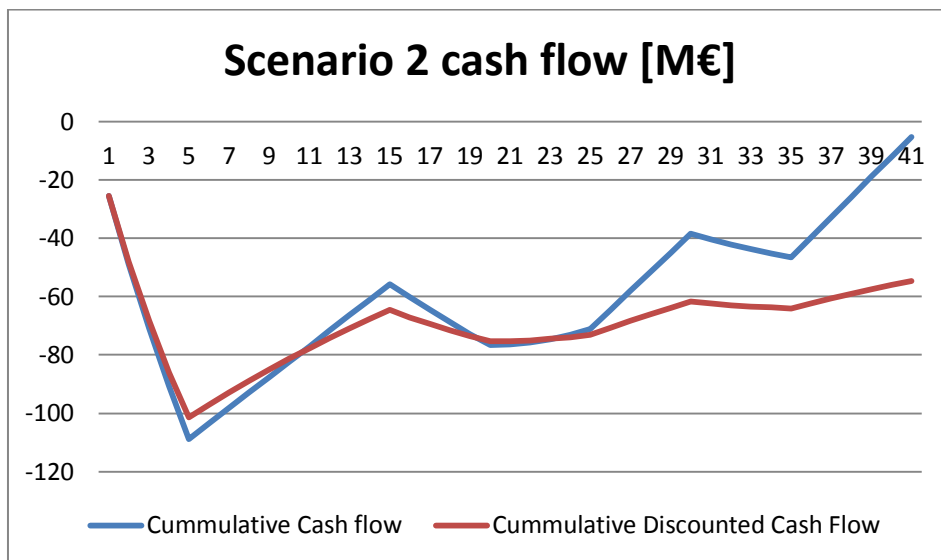
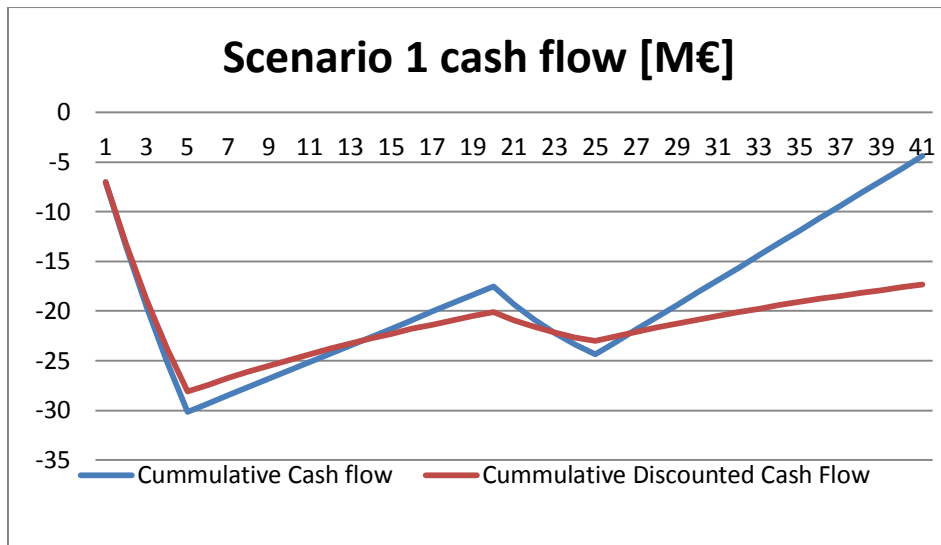


Figure 33. Cash flow of the 3 scenarios in [M€]

7.3. CO₂ mitigation costs

In order to convert all current and future profits and losses to the present situation and count them together the net present value (NPV) of each scenario is calculated. The NPV is summarized in the following formula:

$$NPV = \sum_{i=0}^n \frac{B_i - C_i}{(1 + r)^i}$$

where:

- NPV = net present value of the project in year 0
- B_i = the benefits or profits of the project in year i
- C_i = the costs or losses of the project in year i, including Capex
- r = discount rate, which in this case is set to 4%, which is a typical value for these kind of projects
- n = lifetime of the project

The NPV is then divided by the CO₂ emissions reduction to obtain the specific mitigation cost for each scenario. The results are summarized in Table 11. As it can be seen from the table the second scenario seems to have the lower cost per emissions mitigated. This scenario also increased the level of energy neutrality and emissions reduction more in relation to the previous scenario than the last one. It is also notable the low benefits and high costs of the first scenario.

Table 11. Energy neutrality and cost per CO₂ reduction for all scenarios

| Scenario | Energy neutrality | CO ₂ reduction | Cost /t CO ₂ |
|-----------------------|-------------------|---------------------------|-------------------------|
| 1. Max. PV | 5% | 9% | € 50 |
| 2. WT, Grid solutions | 32% | 54% | € 22 |
| 3. HP, EV, EMS | 38% | 63% | € 38 |

If the scenarios are analyzed as steps, so as if after implementing scenario 1, extra solutions were implemented to achieve scenario 2, and then scenario 3, thus analyzing the extra costs and benefits of scenario 2, in relation with scenario 1, and doing the same with scenario 3, the results are more impressive. Then the extra CO₂ emissions reductions achieved with scenario 2 would cost €17 euros per tonne, but for scenario 3 goes up to €133 per tonne (as shown in Figure 3). This gives a better idea of how costly or profitable the solutions can be in relation with the first approach of achieving the goal with only PVs.

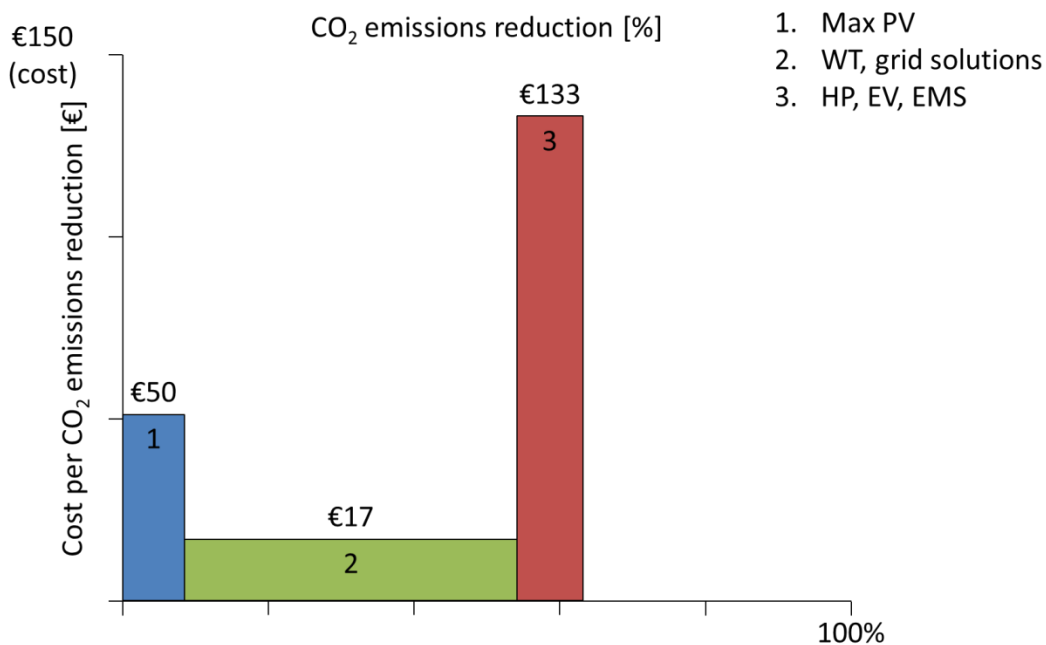


Figure 34. Abatement curve of cost of CO₂ mitigation in € per tonne of CO₂ emission reduction per scenario

Scenarios 2 and 3 are composed by a set of solutions. For a further analysis, each solution was analyzed in the same way, as if they were implemented in steps. Figure 35 includes the results of this analysis. Going deeper into the analysis of the scenarios it can be noted that from scenario 2, the wind turbines, cable-pooling, and use of the backup installation can be profitable, while the 10% electricity curtailment is costly. For scenario 3, it is also interesting to see the differences between implementing only heat pumps and electric vehicles and combining them with an energy management system. For this case it is highly beneficial to always include an EMS to decrease the cost. In this figure the option of investing in the grid instead of implementing the innovative solutions is also assessed. The cost of this option, estimated based on previous Alliander projects, would be of M€16,5 which results in an overall similar cost than of scenario 2. Analyzing it separately, investing in the grid is more expensive than wind turbines, cable-pooling, and the use of the backup installation, but cheaper than electricity curtailment.

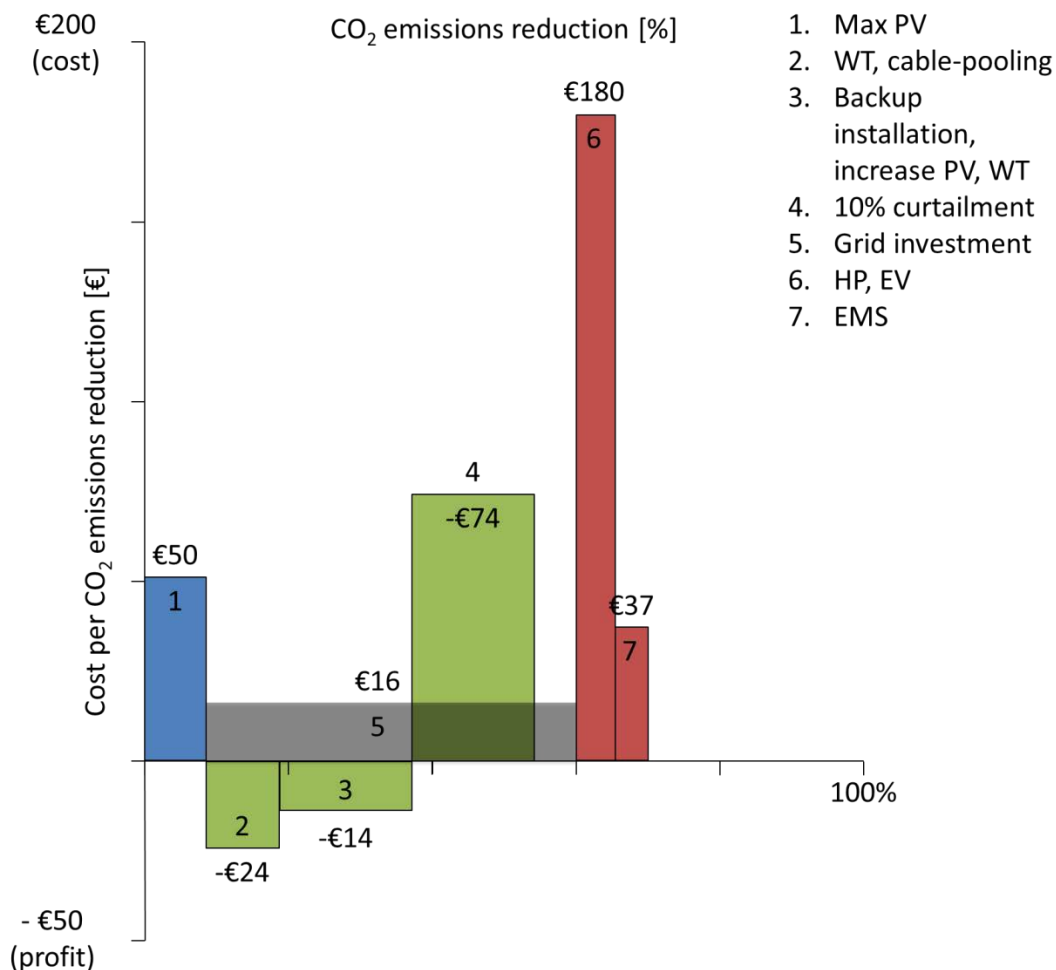


Figure 35. Abatement curve of cost of CO₂ mitigation in € per tonne of CO₂ emissions reduction per solution

All the scenarios were calculated assuming that electricity export is possible. This might be the case now, but is uncertain whether or not this will be possible in the future at its totality. To assess the impact of this uncertainty, a sensitivity analysis was done and the results are included in Figure 36. For the calculations of none electricity exports, it was just assumed that €0 euros were received for these electricity, and 0 credits for the tonnes of CO₂ emissions that would have been avoided. No other cost is included to handle this extra electricity.

In this assessment the first approach from Texel was also included. This approach is explained in Chapter 4, and consists of achieving 60% energy neutrality with only PVs. From this analysis is clear that the original Texel's approach is more expensive and more risky. The risk is because of the high amount of electricity exports. Comparing scenario 2 and 3, even if scenario 3 is in general more expensive has a lower risk in this topic than scenario 2.

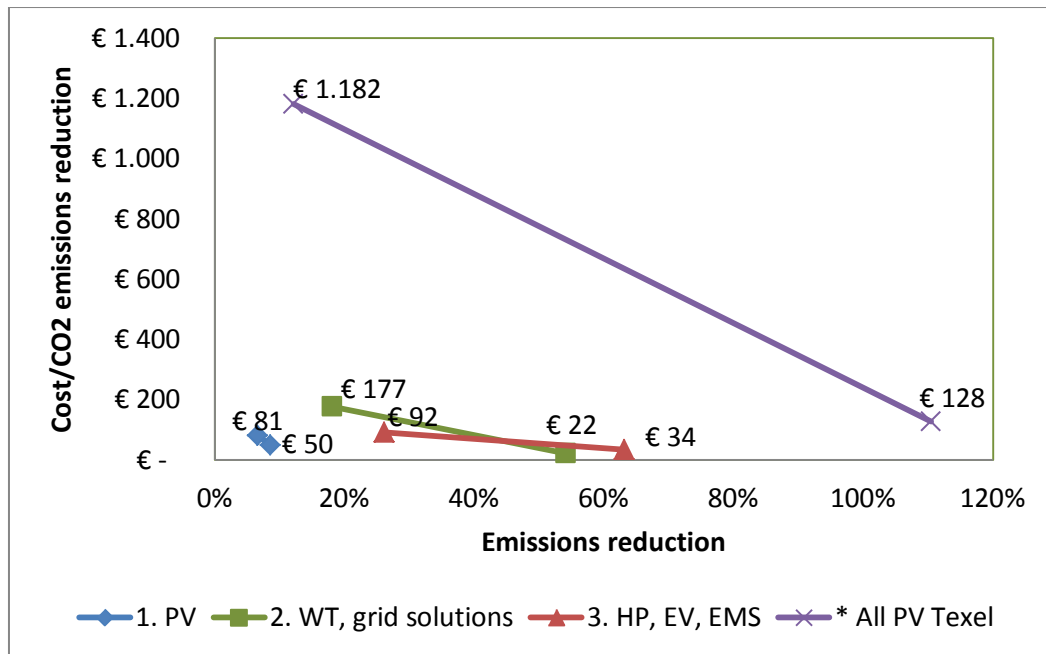


Figure 36. Cost-benefits without (left) and with (right) exports

Chapter 8. Conclusions and further studies

The benefits of installing only PV panels are low and costly; comparing the remaining scenarios it is clear that the alternative solutions on the grid management and the addition of wind power can bring the greatest benefits in terms of overall costs per CO₂ reductions and level of energy neutrality. While the third scenario does bring extra CO₂ emissions these come on a relative high cost and does not increase the level of energy neutrality significantly.

Comparing the three scenarios, the second is the best option. Simple changes on the grid are profitable. But a deeper analysis shows that the low cost of the wind turbines is the most influential in the overall low cost; and not all grid solutions affect the cost positively. While cable-pooling and use of backup installation are profitable, the electricity curtailment is costly, at least at that level.

Increasing grid capacity has similar cost/CO₂ reduction than scenario two, and seems even cheaper than 10% electricity curtailment, but increases the dependency with the mainland, which goes against Texel's goal and increases uncertainty for future exports.

Residential demand-supply matching is costly and uncertain, and the benefits are low compared with the rest of the solutions. The high costs are mainly due to the high investment to replace the HP and EV in a short time. However, if the replacement is done after the actual lifetime of the current equipment, there will be no extra expenses and the overall cost will be reduced dramatically. This on the other hand would delay the benefits obtained. An EMS helps to lower the high costs of the electrification of space heating and private transport, in case of opting for this solutions, it is more beneficial to include EMS to lower the costs.

Further studies related to options to replace curtailment can include the implementation of batteries and the analysis of possible demand flexibility on commercial applications. Batteries can also be used in order to warrantee electricity security on the island, to potentially be able to increase the import capacity by using the backup installation not only for electricity exports but also for imports.

Adding diversity of sources can be beneficial, solutions such as underground energy and geothermal energy should be assessed; as well as improvement of energy efficiency in buildings.

Optimization of the combination of PV and wind turbines capacities would increase benefits and reduce costs. Further analysis on more detailed storage can also improve the results but might also increase uncertainty due to the external factors affecting the actual real-time necessities.

Further cost-benefits analysis per stakeholder can be done to estimate the impact on each. Such analysis would be on shorter term due to uncertainties of RES conditions in the future years.

Considering the benefits and costs assessed on this study, the best option for Texel consists of the following:

- PV installation of 30 MW
- Wind turbine installation of 30 MW
- Cable-pooling
- Use of backup installation

Such a system would bring a 37% decrease of CO₂ emissions, and would achieve a level of energy neutrality of 22%. The CO₂ emissions mitigation would not have a cost, but this would result on a profit of 0,6% on energy expenses. The next steps would be to find an optimal combination of PV and wind turbines and a curtailment percentage to increase the benefits.

Finally, looking at the results it can be concluded that in this case a smart design is more effective than a smart grid. This does not mean that a smart grid should be discharged but that there might be other solutions that should be considered before this. The solutions from the second scenario are the most recommendable; the focus should be first on implementing these changes that are rather simple.

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Appendix I. Texel's extra information

a. Population

The area of Den Burg is the denser in population as can be seen in Figure 37, followed by De Koog and Oudeschild.

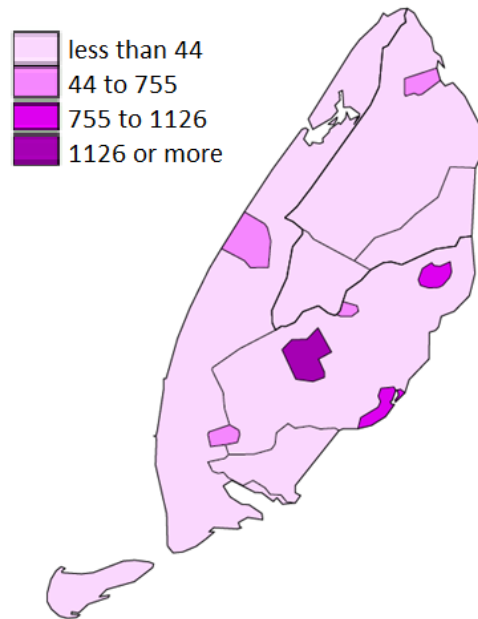
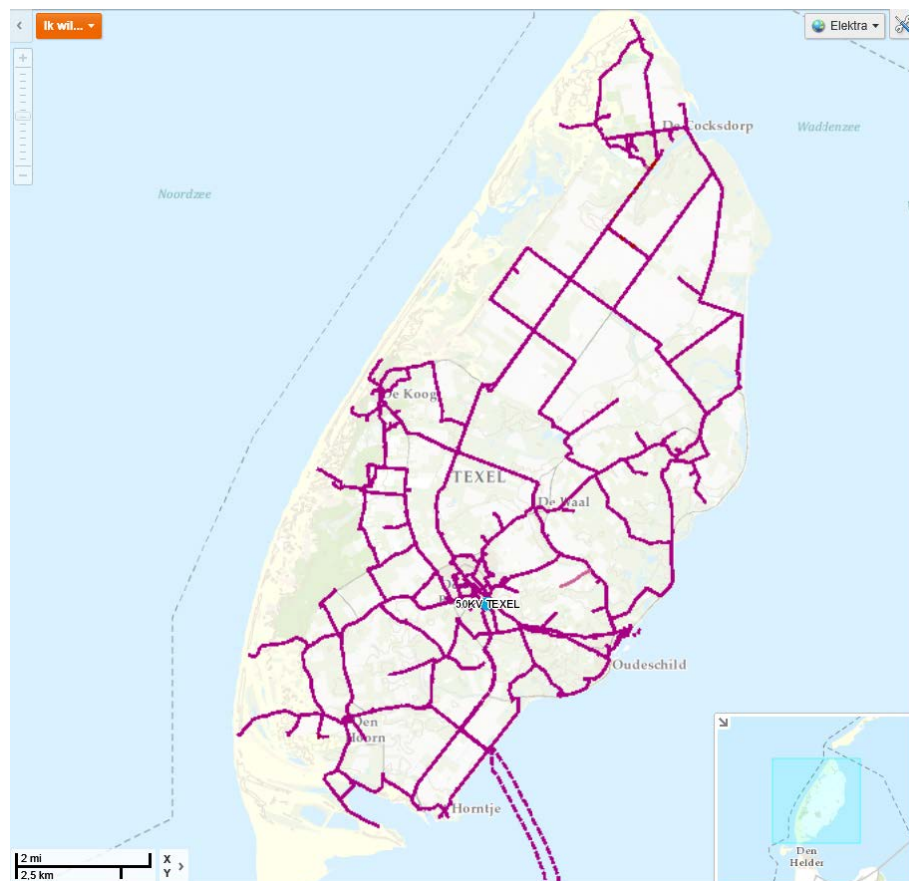


Figure 37. Number of habitants per km² [8]



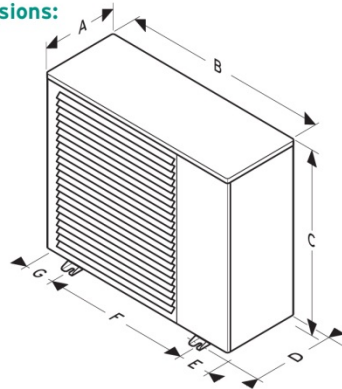
Appendix II. Technical specifications of the heat pump

aroTHERM air to water heat pump technical data



| Article No. | Vaillant parts |
|-------------|---------------------------------------|
| 0020196231 | aroTHERM 5kW pack |
| 0020175478 | aroTHERM 8kW pack |
| 0020175479 | aroTHERM 11kW pack |
| 0020196232 | aroTHERM 15kW pack |
| 0020165288 | 750mm flexi hose |
| 0020175140 | 600mm anti-vibration feet |
| 0020145563 | glycol discharge vessel |
| 0020177865 | aroTHERM 40ltrs buffer de-coupler mod |
| 0020145030 | back up heater |
| 0020143800 | Hex module |
| Article No. | aroTHERM Hybrid systems |
| 0020196235 | aroTHERM 5kW hybrid |
| 0020178074 | aroTHERM 8kW hybrid |
| 0020178075 | aroTHERM 11kW hybrid |
| 0020196236 | aroTHERM 15kW hybrid |
| 0020196233 | aroTHERM 5kW hybrid (for VL boiler) |
| 0020178072 | aroTHERM 8kW hybrid (for VL boiler) |
| 0020178073 | aroTHERM 11kW hybrid (for VL boiler) |
| 0020196234 | aroTHERM 15kW hybrid (for VL boiler) |

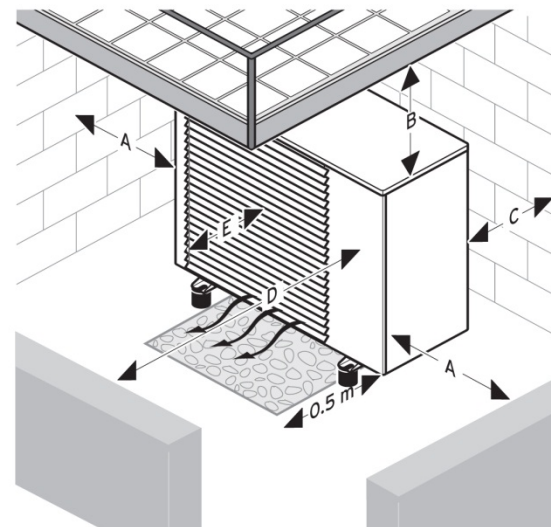
Dimensions:



| Dimension | 5kW | 8kW | 11kW | 15kW |
|-----------|-----|------|------|------|
| A | 408 | 463 | 463 | 463 |
| B | 980 | 1103 | 1103 | 1103 |
| C | 840 | 975 | 975 | 1380 |
| D | 386 | 437 | 437 | 437 |
| E | 120 | 162 | 162 | 162 |
| F | 740 | 778 | 778 | 778 |
| G | 120 | 162 | 162 | 162 |

| | | Outdoor temp | 5kW | 8kW | 11kW | 15kW |
|--|------|--------------|------|-------|-------|-------|
| Flow 35°C MCS 6 star system | -5°C | kW | 5.00 | 7.32 | 8.23 | 12.65 |
| | | CoP | 2.82 | 2.83 | 2.66 | 2.75 |
| | -3°C | kW | 5.00 | 7.70 | 8.42 | 12.90 |
| | | CoP | 3.01 | 2.91 | 2.75 | 3.00 |
| | 0°C | kW | 5.00 | 7.81 | 9.25 | 13.20 |
| | | CoP | 3.25 | 3.12 | 2.97 | 3.20 |
| 2°C | kW | 5.00 | 8.27 | 9.81 | 14.00 | |
| | CoP | 3.40 | 3.38 | 3.20 | 3.30 | |
| 7°C | kW | 5.00 | 8.41 | 11.20 | 14.60 | |
| | CoP | 4.67 | 4.75 | 4.25 | 4.46 | |
| Flow 45°C MCS 4 star system | -5°C | kW | 5.00 | 5.84 | 7.17 | 11.00 |
| | | CoP | 2.10 | 2.31 | 2.16 | 2.43 |
| | -3°C | kW | 5.00 | 5.98 | 7.30 | 11.50 |
| | | CoP | 2.38 | 2.40 | 2.19 | 2.60 |
| | 0°C | kW | 5.00 | 6.58 | 7.88 | 12.40 |
| | | CoP | 2.56 | 2.57 | 2.35 | 2.80 |
| anything over a 3 star system cannot get RHI | | | | | | |
| Flow 55°C MCS 2 star system | -5°C | kW | 4.36 | 4.41 | 5.61 | 9.90 |
| | | CoP | 1.61 | 1.89 | 1.64 | 2.22 |
| | -3°C | kW | 4.50 | 4.72 | 6.00 | 10.30 |
| | | CoP | 1.85 | 1.97 | 1.72 | 2.23 |
| | 0°C | kW | 5.00 | 5.37 | 6.70 | 11.20 |
| | | CoP | 2.00 | 2.45 | 1.90 | 2.40 |

Clearances:



| Clearance | For Heating Mode |
|-----------|------------------|
| A | > 250mm |
| B | > 1000mm |
| C | > 120mm |
| D | > 600mm |
| E | > 300mm |

Appendix III. Matlab model to define maximum HP and EV capacity with fixed profiles.

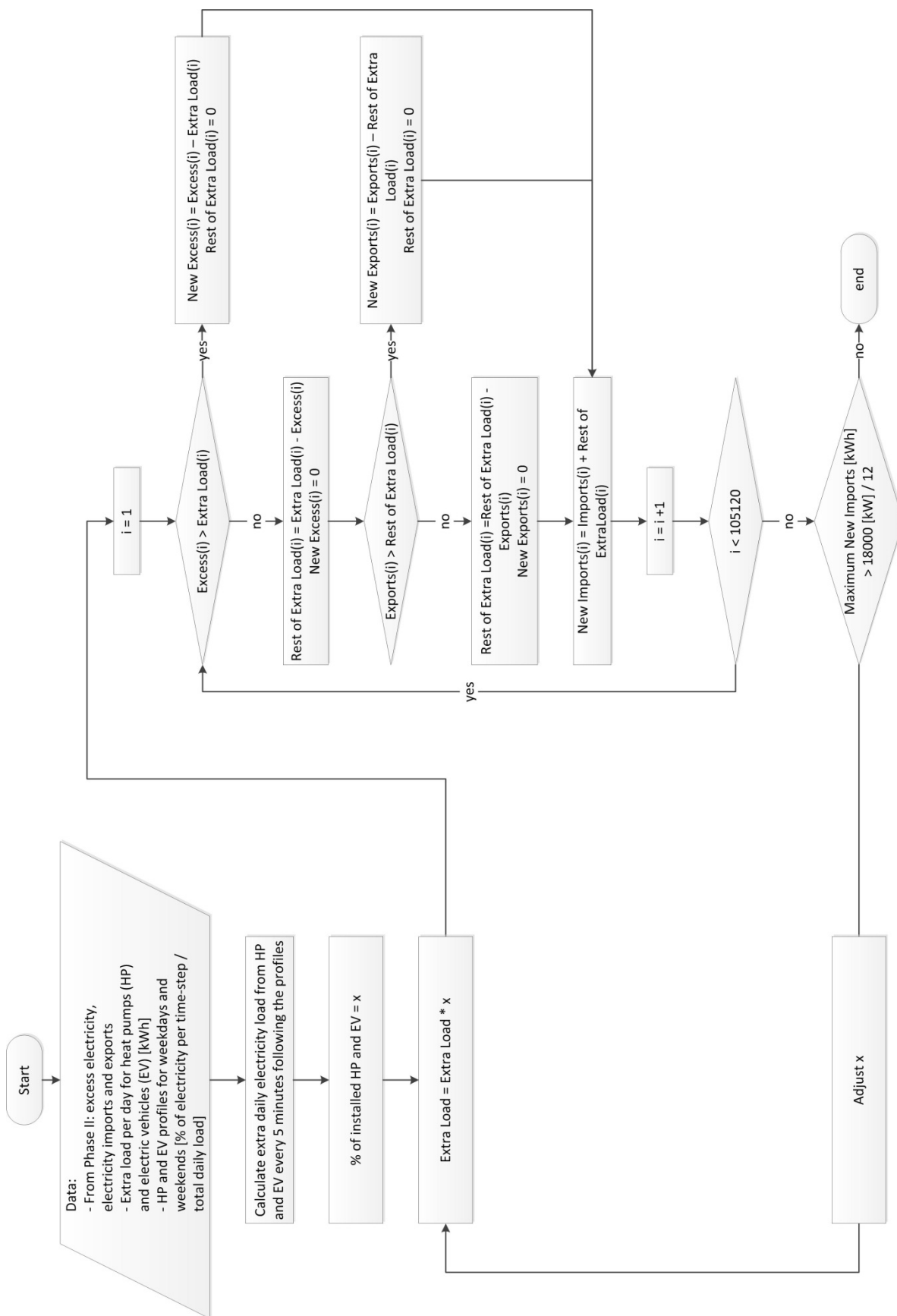


Figure 38. Flow diagram of Matlab model to distribute extra load based on fixed profiles

```

%% Import data from spreadsheet
% Script for importing data from the following spreadsheet:
%
%   Workbook: D:\Desktop\Matlab_data\Extra load per day.xlsx
Worksheet:
%   Sheet1
%
% To extend the code for use with different selected data or a
different
% spreadsheet, generate a function instead of a script.

% Auto-generated by MATLAB on 2014/10/24 08:53:44

%% Import the data
[~, ~, raw0_0] = xlsread('D:\Desktop\Matlab_data\Extra load per
day.xlsx','Sheet1','B1:C366');
[~, ~, raw0_1] = xlsread('D:\Desktop\Matlab_data\Extra load per
day.xlsx','Sheet1','H1:I366');
raw = [raw0_0,raw0_1];
raw(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),raw)) =
{' '};

%% Replace non-numeric cells with NaN
R = cellfun(@(x) ~isnumeric(x) && ~islogical(x),raw); % Find non-
numeric cells
raw(R) = {NaN}; % Replace non-numeric cells

%% Create output variable
data = reshape([raw{:}],size(raw));

%% Create dataset array
Extraloadperday = dataset;

%% Allocate imported array to column variable names
Extraloadperday.MM = data(:,1);
Extraloadperday.DD = data(:,2);
Extraloadperday.HP kWh = data(:,3);
Extraloadperday.EV kWh = data(:,4);

%% Clear temporary variables
clearvars data raw raw0_0 raw0_1 R;

%%load profiles
load('EV_HP_Profiles.mat')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
InstalledEVHP = 0.42%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%Create variables
EVDailyLoad = Extraloadperday.EV kWh(2:366)*InstalledEVHP;
HPDailyLoad = Extraloadperday.HP kWh(2:366)*InstalledEVHP;
MM = Extraloadperday.MM(2:366);
DD = Extraloadperday.DD(2:366);

```



```

        for minute = 1:288;
            HPstep = (i-1)*288 + minute;
            HPConsum(HPstep) =
HPProfileWeekend(minute)/100 * HPDailyLoad(i);
        end
    else
        for minute = 1:288;
            HPstep = (i-1)*288 + minute;
            HPConsum(HPstep) =
HPProfileWeekdays(minute)/100 * HPDailyLoad(i);
        end
    end
end
end
end
end
end
end

%Check daily values

%Fix daily values

PreDailyHP = zeros (365,1);

for i = 1:365;
    a = 288*(i-1) + 1;           %first 5-minute of the day
    b = a +287;                 %last 5-minute of the day
    PreDailyHP(i) = sum(HPConsum(a:b));
end

%% include (fixed) EV and HP in the system
load('Initial_Data.mat')
PreConsum = minkWh.Consum + EVConsum + HPConsum;
PreExcess = minkWh.Excess;
PreExports = minkWh.Exports;
PreImports = minkWh.Imports;

%Fix 5 min values
ExtraLoad = EVConsum + HPConsum;
PreExtraLoad = ExtraLoad; %ExtraLoad remains with original values,
PreExtraLoad is 0 at the end
for i = 1:105120;
    if PreExcess(i) > PreExtraLoad(i);
        PreExcess(i) = PreExcess(i) - PreExtraLoad(i);
        PreExtraLoad(i) = 0;
    else
        PreExtraLoad(i) = PreExtraLoad(i) - PreExcess(i);
        PreExcess(i) = 0;
        if PreExports(i) > PreExtraLoad(i);
            PreExports(i) = PreExports(i) - PreExtraLoad(i);
            PreExtraLoad(i) = 0;
        else
            PreExtraLoad(i) = PreExtraLoad(i) - PreExports(i);
            PreExports(i) = 0;
            PreImports(i) = PreImports(i) + PreExtraLoad(i);
            PreExtraLoad(i) = 0;
        end
    end
end

```

```

end
end

%Fix daily values

PreDailyExcess = zeros (365,1);
PreDailyExports = zeros (365,1);
PreDailyImports = zeros (365,1);
PreDailyConsum = zeros (365,1);
PreDailyExtraLoad = zeros (365,1); %OK

for i = 1:365;
    a = 288*(i-1) + 1;           %first 5-minute of the day
    b = a + 287;               %last 5-minute of the day
    PreDailyExcess(i) = sum(PreExcess(a:b));
    PreDailyExports(i) = sum(PreExports(a:b));
    PreDailyImports(i) = sum(PreImports(a:b));
    PreDailyConsum(i) = sum(PreConsum(a:b));
    PreDailyExtraLoad(i) = sum(EVConsum(a:b)) + sum(HPConsum(a:b));
end

%%Check import capacity

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
ImportCap = (18000)/12;      %           Maximum import capacity in kWh
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
UnmetLoad = 0;
CountUnmetLoad = 0;

for i = 1:105120;
    if PreImports(i) > ImportCap;
        UnmetLoad = UnmetLoad + PreImports(i) - ImportCap;
        CountUnmetLoad = CountUnmetLoad + 1;
    end
end

if UnmetLoad > 0;
    warning('NewImports exceedss maximum imports %i times, the total
unmet load is %i', CountUnmetLoad, UnmetLoad);
end

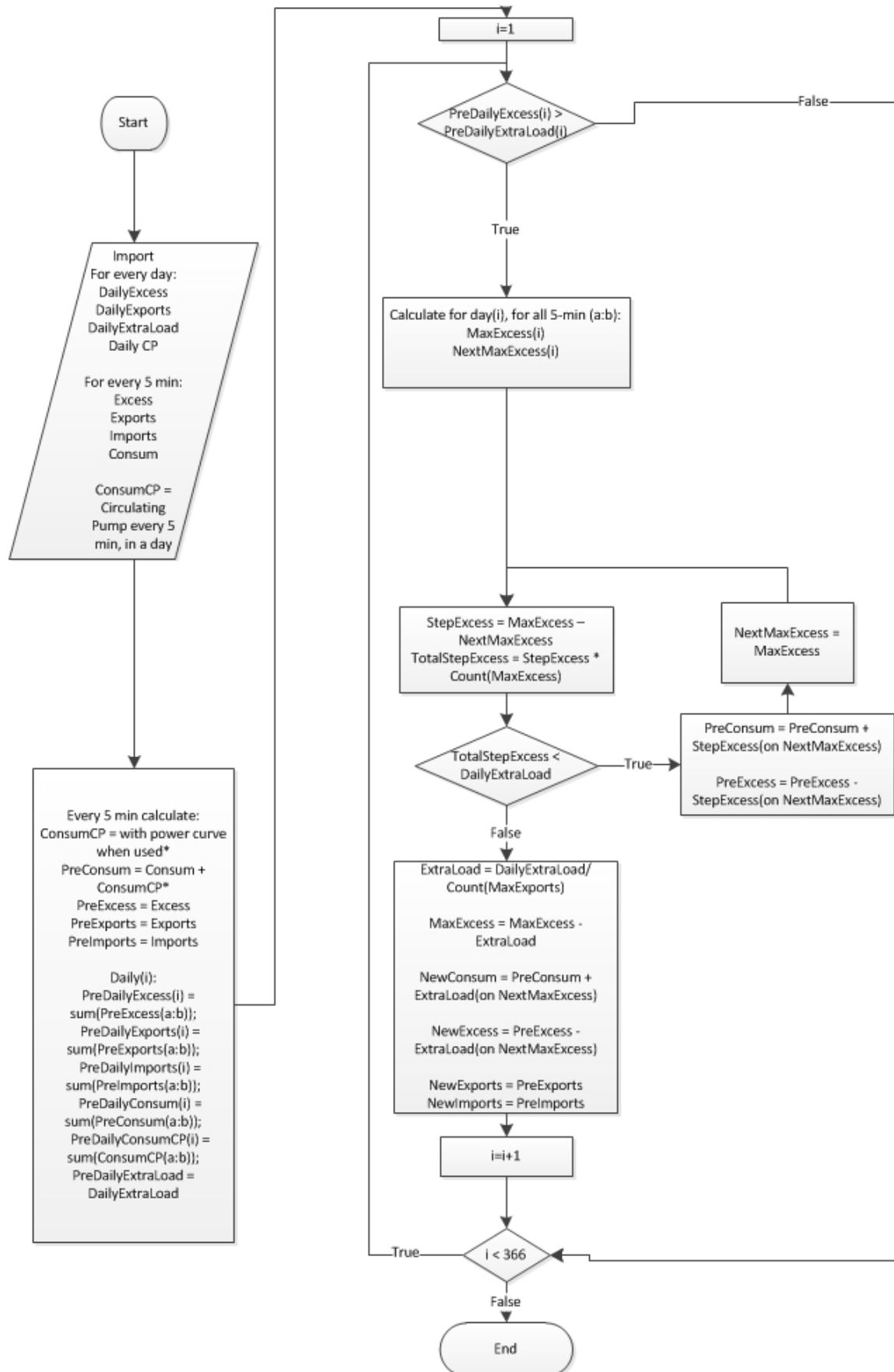
%% Data for Homer, New Consumption in kW
NewConsumkW = PreConsum .*12;

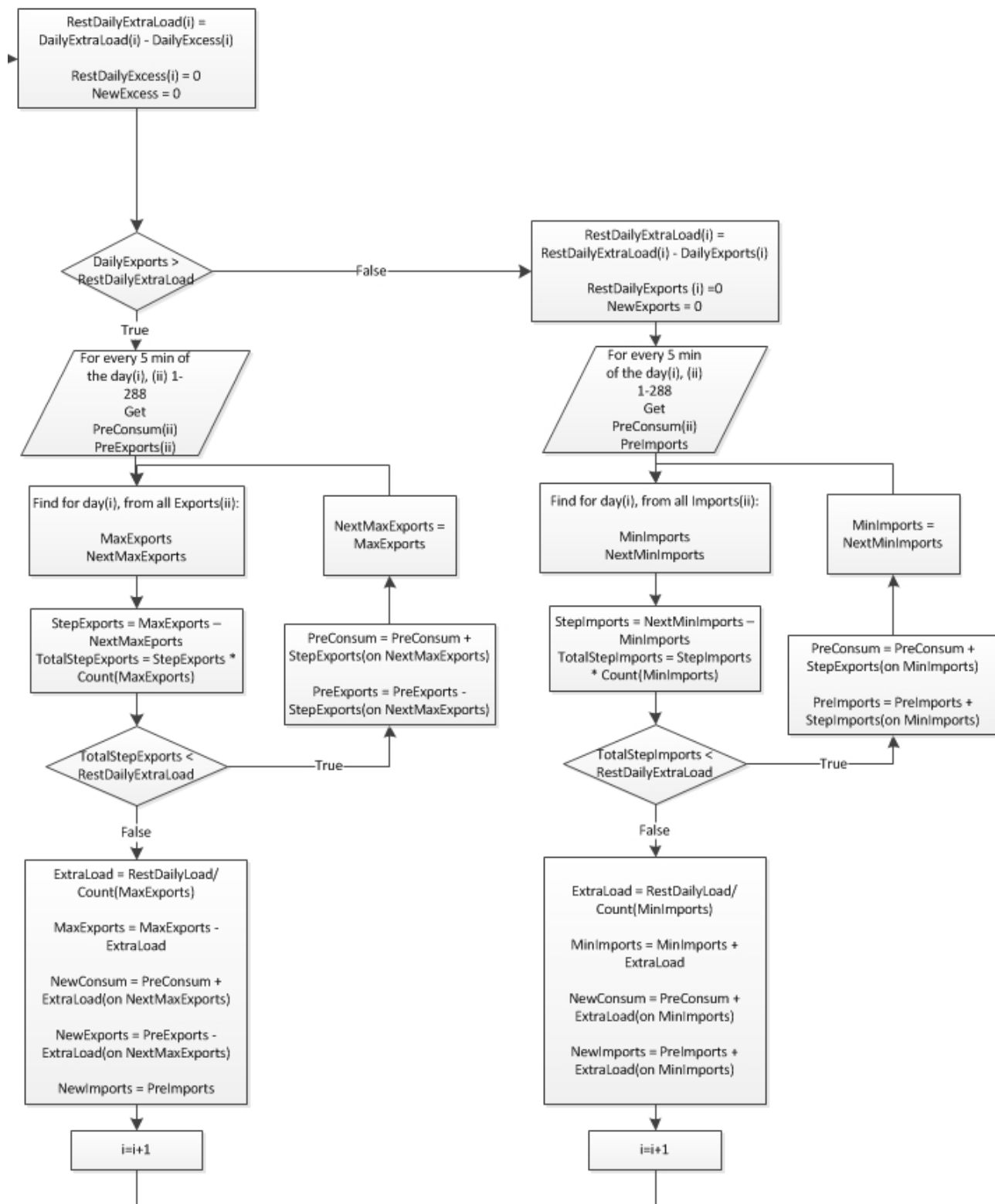
xlswrite('NewLoad_EV_HP_fixed.xlsx', NewConsumkW)

```

Appendix IV. Matlab model for phase 3.

Flow diagram





Matlab code

```

%%Import data (3)
%% Import data from spreadsheet
% Script for importing data from the following spreadsheet:
%
%   Workbook: C:\Users\bwlpmckula\Dropbox\SEBC\Alliander
%   assignment\data\Matlab_data\Daily_kWh.xls Worksheet: phase 3,
%   100%HP,EV
%
% To extend the code for use with different selected data or a
different
% spreadsheet, generate a function instead of a script.

% Auto-generated by MATLAB on 2014/10/10 15:54:53

%% Import the data
[~, ~, raw] = xlsread('D:\Desktop\Matlab_data\Daily_kWh.xls', 'phase
3, 100%HP,EV', 'A2:F366');

%% Create output variable
data = reshape([raw{:}],size(raw));

%% Create dataset array
DailykWh = dataset;

%% Allocate imported array to column variable names
DailykWh.MM = data(:,1);
DailykWh.DD = data(:,2);
DailykWh.DailyExports = data(:,3);
DailykWh.DailyExcess = data(:,4);
DailykWh.DailyExtraLoad = data(:,5);
DailykWh.DailyCP = data(:,6);

%% Clear temporary variables
clearvars data raw;

%% Import data from spreadsheet
% Script for importing data from the following spreadsheet:
%
%   Workbook: C:\Users\bwlpmckula\Dropbox\SEBC\Alliander
%   assignment\data\Matlab_data\5min_kWh.xlsx Worksheet: hourly
%
% To extend the code for use with different selected data or a
different
% spreadsheet, generate a function instead of a script.

% Auto-generated by MATLAB on 2014/10/10 16:15:06

%% Import the data
[~, ~, raw] =
xlsread('D:\Desktop\Matlab_data\5min_kWh.xlsx', 'hourly', 'A2:G105121')
;
raw(cellfun(@(x) ~isempty(x) && isnumeric(x) && isnan(x),raw)) =
{' '};

%% Replace non-numeric cells with NaN
R = cellfun(@(x) ~isnumeric(x) && ~islogical(x),raw); % Find non-
numeric cells
raw(R) = {NaN}; % Replace non-numeric cells

```

```

%% Create output variable
data = reshape([raw{:}],size(row));

%% Create dataset array
minkWh = dataset;

%% Allocate imported array to column variable names
minkWh.MM = data(:,1);
minkWh.DD = data(:,2);
minkWh.Time = data(:,3);
minkWh.Excess = data(:,4);
minkWh.Exports = data(:,5);
minkWh.Imports = data(:,6);
minkWh.Consum = data(:,7);

%% Clear temporary variables
clearvars data row R;

%% Import data from spreadsheet
% Script for importing data from the following spreadsheet:
%
%   Workbook: C:\Users\bwlpmckula\Dropbox\SEBC\Alliander
%   assignment\data\Matlab_data\TotalConsumCP.xlsx Worksheet: Sheet1
%
% To extend the code for use with different selected data or a
different
% spreadsheet, generate a function instead of a script.

% Auto-generated by MATLAB on 2014/10/10 16:39:07

%% Import the data
[~, ~, row] = xlsread('C:\Users\bwlpmckula\Dropbox\SEBC\Alliander
assignment\data\Matlab_data\TotalConsumCP.xlsx','Sheet1','A2:B289');

%% Create output variable
data = reshape([row{:}],size(row));

%% Create dataset array
TotalConsumCP = dataset;

%% Allocate imported array to column variable names
TotalConsumCP.Min = data(:,1);
TotalConsumCP.CP = data(:,2);

%% Clear temporary variables
clearvars data row;

%%Calculate Consumption of Circulating Pump, every 5 min
ConsumCP = zeros (105120,1);
for i = 1:365;
    for month = 1:12;
        if DailykWh.MM(i) == month;
            for day = 1:31;
                if DailykWh.DD(i) == day
                    if DailykWh.DailyCP(i) > 0;
                        for minute = 1:288;

```



```

        CP = (i-1)*288 + minute;
        ConsumCP(CP) = TotalConsumCP.CP(minute);
    end
    else
        CP = (i-1)*288 + minute;
        ConsumCP(CP) = 0;
    end
end
end
end
end
end
end

%%Create intermediate variables
PreConsum = minkWh.Consum + ConsumCP;
PreExcess = minkWh.Excess;
PreExports = minkWh.Exports;
PreImports = minkWh.Imports;

%%Fix variables to include consumption of Circulating Pump
%%Fix 5 min values
PreConsumCP = ConsumCP; %ConsumCP remains with original values,
PreConsumCP is 0 at the end
for i = 1:105120;
    if PreExcess(i) > PreConsumCP(i);
        PreExcess(i) = PreExcess(i) - PreConsumCP(i);
        PreConsumCP(i) = 0;
    else
        PreConsumCP(i) = PreConsumCP(i) - PreExcess(i);
        PreExcess(i) = 0;
    if PreExports(i) > PreConsumCP(i);
        PreExports(i) = PreExports(i) - PreConsumCP(i);
        PreConsumCP(i) = 0;
    else
        PreConsumCP(i) = PreConsumCP(i) - PreExports(i);
        PreExports(i) = 0;
        PreImports(i) = PreImports(i) + PreConsumCP(i);
        PreConsumCP(i) = 0;
    end
end
end
end

%%Fix daily values

PreDailyExcess = zeros (365,1);
PreDailyExports = zeros (365,1);
PreDailyImports = zeros (365,1);
PreDailyConsum = zeros (365,1);
PreDailyConsumCP = zeros (365,1);

for i = 1:365;
    a = 288*(i-1) + 1; %first 5-minute of the day
    b = a +287; %last 5-minute of the day
    PreDailyExcess(i) = sum(PreExcess(a:b));
    PreDailyExports(i) = sum(PreExports(a:b));
    PreDailyImports(i) = sum(PreImports(a:b));
    PreDailyConsum(i) = sum(PreConsum(a:b));
    PreDailyConsumCP(i) = sum(ConsumCP(a:b));
end
%OK

```

```

%Data ready

%%Include HP and EV
%First check up: daily values

PreDailyExtraLoad = DailykWh.DailyExtraLoad;
PreExtraLoad = zeros(105120,1);
ExtraLoad = zeros(105120,1);
NewConsum = zeros(105120,1);
NewExcess = zeros(105120,1);
NewExports = zeros(105120,1);
NewImports = zeros(105120,1);
NewDailyExcess = zeros (365,1);
NewDailyExports = zeros (365,1);
NewDailyImports = zeros (365,1);
NewDailyConsum = zeros (365,1);
%%

for i=1:365; %To do it for every day of the
year %first 5-minute of the day
    a = 288*(i-1) + 1; %last 5-minute of the day
    b = a +287;

    if PreDailyExcess(i)>PreDailyExtraLoad(i); %If DailyExcess is
enough for all DailyExtraLoad
        SortDay = unique(PreExcess(a:b)); %NOT 'descend' because
for Freq has to be ascend
            y = length(SortDay);

            Steps = zeros(y,1);

            Freq = histc(PreExcess(a:b),SortDay);
            SortDay = flipud(SortDay); %sort SortDay and Freq
            Freq = flipud(Freq);
            Steps(1:y-1)= -diff(SortDay); %get 'size'
of each step
            Steps(y) = SortDay(y);
            CumFreq = cumsum(Freq); %cumulative
frequency
            TotalSteps = cumsum(Steps .* CumFreq); %cumulative
electricity of all steps
            DiffStepsELoad = TotalSteps - PreDailyExtraLoad(i);

            [~, idx] = min(abs(DiffStepsELoad)); %New
MaxExports index (approx)
            if DiffStepsELoad(idx)>0 && idx > 1;
                idx = idx-1;
            end

            NewMaxExcess = SortDay(idx+1)-(-
(DiffStepsELoad(idx))/CumFreq(idx+1));

            for minute=a:b;
%fix 5-min values NewExcess
                if PreExcess(minute) > NewMaxExcess;
                    ExtraLoad(minute) = (PreExcess(minute)-NewMaxExcess);
                    NewExcess(minute) = NewMaxExcess;
                else

```

```

        ExtraLoad(minute) = 0;
        NewExcess(minute) = PreExcess(minute);
    end
    NewConsum(minute) = PreConsum(minute) +
ExtraLoad(minute);
    NewExports(minute) = PreExports(minute);
    NewImports(minute) = PreImports(minute);
end

    NewDailyExcess(i) = sum(NewExcess(a:b));    %fix daily values
    NewDailyExports(i) = sum(NewExports(a:b));
    NewDailyImports(i) = sum(NewImports(a:b));
    NewDailyConsum(i) = sum(NewConsum(a:b));
    %%%%%%%%%

else
    PreDailyExtraLoad(i) = PreDailyExtraLoad(i) -
PreDailyExcess(i);    %use first ALL Excess

        if PreDailyExports(i)>PreDailyExtraLoad(i);    %if Daily Excess
is not enough, start using exports
            SortDay = unique(PreExports(a:b));    %NOT 'descend'
because for Freq has to be ascend
            y = length(SortDay);

            Steps = zeros(y,1);

            Freq = histc(PreExports(a:b),SortDay);
            SortDay = flipud(SortDay);    %sort SortDay and
Freq
            Freq = flipud(Freq);
            Steps(1:y-1) = -diff(SortDay);    %get
'size' of each step
            Steps(y) = SortDay(y);
            CumFreq = cumsum(Freq);    %cumulative
frequency
            TotalSteps = cumsum(Steps .* CumFreq);    %cumulative
electricity of all steps
            DiffStepsELoad = TotalSteps - PreDailyExtraLoad(i);

            [~, idx] = min(abs(DiffStepsELoad));    %New
MaxExports index (approx)
            if DiffStepsELoad(idx)>0 && idx > 1;
                idx = idx-1;
            end

            NewMaxExports = SortDay(idx+1)-(-
(DiffStepsELoad(idx))/CumFreq(idx+1));

        for minute=a:b;
%fix 5-min values NewExcess
            if PreExports(minute) > NewMaxExports;
                ExtraLoad(minute) = (PreExports(minute)-
NewMaxExports) + PreExcess(minute);
                NewExports(minute) = NewMaxExports;
            else
                ExtraLoad(minute) = PreExcess(minute);
                NewExports(minute) = PreExports(minute);
            end
end

```

```

        NewConsum(minute) = PreConsum(minute) +
ExtraLoad(minute);
        NewExcess(minute) = 0;
        NewImports(minute) = PreImports(minute);
    end

        NewDailyExcess(i) = sum(NewExcess(a:b));
%fix daily values
        NewDailyExports(i) = sum(NewExports(a:b));
        NewDailyImports(i) = sum(NewImports(a:b));
        NewDailyConsum(i) = sum(NewConsum(a:b));
        %%%%%%%%%

    else
%if Daily Exports is not enough, import the rest

        PreDailyExtraLoad(i) = PreDailyExtraLoad(i) -
PreDailyExports(i);

        FreeImports = max(PreImports(a:b))- PreImports(a:b);
        SortDay = unique(FreeImports); %NOT 'descend' because
for Freq has to be ascend
        y = length(SortDay);

        Steps = zeros(y,1);

        Freq = histc(FreeImports,SortDay);
        SortDay = flipud(SortDay); %sort SortDay and
Freq
        Freq = flipud(Freq);
        Steps(1:y-1)= -diff(SortDay); %get
'size' of each step
        Steps(y) = SortDay(y);
        CumFreq = cumsum(Freq); %cumulative
frequency
        TotalSteps = cumsum(Steps .* CumFreq); %cumulative
electricity of all steps

        if TotalSteps(y) < PreDailyExtraLoad(i);
            NewMinImports = max(PreImports(a:b)) +
((PreDailyExtraLoad(i) - TotalSteps(y))/288);
        else

            DiffStepsELoad = TotalSteps - PreDailyExtraLoad(i);

            [~, idx] = min(abs(DiffStepsELoad)); %New
MinImports index (approx)
            if DiffStepsELoad(idx)>0 && idx > 1;
                idx = idx-1;
            end

            NewMaxFreeImports = SortDay(idx+1) - (-
(DiffStepsELoad(idx))/CumFreq(idx+1));
            NewMinImports = max(PreImports(a:b)) -
NewMaxFreeImports;
        end
    end

```

```

        for minute=a:b;
%fix 5-min values NewExcess
            if PreImports(minute) < NewMinImports;
                ExtraLoad(minute) = (NewMinImports -
PreImports(minute)) + PreExcess(minute) + PreExports(minute);
                NewImports(minute)= NewMinImports;
            else
                ExtraLoad(minute) = PreExcess(minute) +
PreExports(minute);
                NewImports(minute) = PreImports(minute);
            end

                NewConsum(minute) = PreConsum(minute) +
ExtraLoad(minute);
                NewExports(minute) = 0;
                NewExcess(minute) = 0;

        end

        NewDailyExcess(i) = sum(NewExcess(a:b));
%fix daily values
        NewDailyExports(i) = sum(NewExports(a:b));
        NewDailyImports(i) = sum(NewImports(a:b));
        NewDailyConsum(i) = sum(NewConsum(a:b));

    end
end
end

```

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