Master's Thesis

Energy Science

GEO4-2510

A broad environmental impact analysis of local energy systems

18-09-2020

Student - Simon Nederhoff
Student number - 5502748
Email - s.r.nederhoff@students.uu.nl, simonnederhoff@gmail.com
Supervisor UU - Prof. dr. Gert Jan Kramer
Second reader - dr. Wen Liu
Internship organization - Alliander N.V.
Internship supervisor - Maarten van Blijderveen. maarten.van.blijderveen@qirion.nl

Abstract

Nations face the need for a decarbonized energy supply, what goes along with the risk that they focus solely on reducing GHG emissions what may occur at the expense of other environmental impacts. Besides GHG emissions, the land requirement and the use of critical resources are considered as relevant in the context of renewable energy systems, as these environmental impacts will increase due to the shift from fossil fuels to renewable energy sources. For these three sustainability indicators, the impact is determined for the neighbourhood 'Haven-Stad', and discussed in relation to sustainable reference values. Also the trade-offs between the sustainability indicators were examined, as well as the effect of a different energy demand. Also the location of the environmental impact categories is researched, for a 100% renewable energy system in comparison to fossil fuel based energy systems.

The results have shown that that the shift from fossil fuels to renewable energy would decrease the GHG emissions of energy systems to levels where the consequences of global warming are manageable. Within renewable energy systems, an exclusive use of intermittent electricity sources is not recommended because it increases the need for energy storage what goes along with the use of critical elements, just as electricity production from intermittent energy sources by solar PV and wind turbines. Therefore, bioenergy could be implemented to provide for non-intermittent electricity, as long as it stays within the sustainable boundaries of land use. Bioenergy predominantly determines the global land use impact of renewable energy systems, while the use of (imported) biomass decreases the land use impact on the place where energy is consumed. This is an example of the externalization of environmental impact, caused by the shift from fossil fuels to renewable energy sources. Due to this externalization, the global impacts need to be taken into account more, and the dependency on countries with large reserves of critical resources increases. This affects the frequently mentioned benefit that renewable energy production increases the independency.

The global upscaling of EVs, battery grid-electricity storage and wind turbines may be hindered by resource depletion of lithium, neodymium and dysprosium. The global resources are sufficient to provide for the required amount of the metals, but it causes that relatively less is available for other applications of the metals than currently. Besides, the annual production of these metals need to increase to implement renewable energy systems on global scale before 2050.

Table of contents

List of abbreviation

BECCS	Bio-Energy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
Cap.	Capita
CCS	Carbon Capture and Storage
CdTe	Cadmium Tellurium
CEEP	Critical Excess Electricity Production
CHP	Combined Heat and Power
CIGS	Copper, Indium, Gallium, Selenium
CO_2-eq.	CO_2-equivalent
COP	Coefficient of performance
c-Si	crystalline silicon
DH	District Heating
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HP	Heat pump
IHH	Individual House Heating
Li-ion	Lithium ion
NdFeB	Neodymium Iron Boron
PP	Power Plant
PV	Photovoltaic

Chapter 1: Introduction

Currently there is a worldwide sustainability challenge to limit the global temperature rise in order to keep the consequences of climate change manageable in the future (Hare, 2012; Knutti et al., 2016). Over the last decades, the recognition of the urgency of climate change and the need for the transition to clean energy has increased, resulting in agreements like the Kyoto protocol and later the 'UN climate agreement of Paris' in which the involved countries have agreed to adhere to the stated greenhouse gas (GHG) emission reduction targets (Hettinga et al., 2018). Based on the Paris agreement, the Dutch government has composed the national climate agreement in cooperation with companies and civil society organizations. In this agreement is stated that GHG emissions need to be reduced by 49% in 2030 and 95% in 2050, both relative to 1990 (Klimaatakkoord, 2019). These targets are specified for five sectors: built environment, mobility, industry, agriculture & land use, and electricity. As the built environment, mobility and electricity sector together are responsible for 55% of the GHG emissions in the Netherlands (CBS, n.d.), local energy systems should play a significant role in the reduction of GHG emissions to achieve the climate goals.

Not only GHG emissions need to be considered as important parameter for sustainability. Other environmental impacts like land use and the use of critical resources are important as well. In literature, policies and regulations about the sustainability of energy supply systems is extensively focussed on the reduction of GHG emissions while other environmental impacts are barely taken into account (Kouloumpis et al., 2015). As the shift to renewable energy sources can result in negative impacts in other sustainability indicators, it is important to incorporate environmental impacts concerning sustainability in the broad context, so beyond GHG emissions (Gibon et al., 2017). The focus on reducing GHG emissions goes along with the risk that climate change mitigation will be carried out at the expense of the remaining environmental impact categories (Kouloumpis et al., 2015).

Besides a broad set of sustainability indicators, the right scale of assessment is important for environmental impact analyses, as well as for reaching the clean energy and climate goals. Zero energy- and emission buildings and neighbourhoods are often put forward as an option to meet sustainability goals (Ala-Juusela, 2016). Although this static building design approach could help reaching the goals, the final design at a broader scope becomes sub-optimal as it will be an assembly of competing solutions resulting in limited grid friendliness concerning load matching of renewable energy flows (Taveres-Cachat et al., 2019). Besides, it indicates that the optimal state of a building or neighbourhood is energy neutrality and being an energy autonomy. Therefore, an interconnected system on a larger scale is preferred as the overall energy system performs more effective and sustainable, although it consists of buildings that individually may not be net energy neutral (Walker et al., 2018; Taveres-Cachat et al.,2019). Applying this argument on a larger scale, it could be argued that not every neighbourhood has to match its demand with their own energy supply. Urban neighbourhoods are more densely populated, require more energy and have less available area for renewable energy production than in rural areas (Bringault et al., 2016). Therefore, local energy systems should be considered as part of a larger (national) energy system instead being an energy autonomy.

For the implementation of energy and planning actions in sustainable city planning, the district level is generally considered as the right scale (Evola et al., 2016). To reach the clean energy and climate goals, local authorities become more important in the European Union's member states because they can find solutions that are better suited to the local context by launching local energy planning activities (Kelly and Pollitt, 2011; Evola et al., 2016). This is also stated in the Dutch climate agreement where the municipalities should play a central role by performing a neighbourhood-oriented approach to reduce the environmental impact from the built environment (Klimaatakkoord, 2019). To drive the changes that are needed for the transition to a sustainable future, many experts believe that defining absolute limits will be necessary. Quantifying these points is by many considered as critical in the management of human impacts (Meyer and Newman, 2020).Therefore it is important to consider sustainable reference values within the assessment of the environmental impact of local energy systems. In existing literature, the environmental impact of renewable energy technologies and systems is generally not analysed in relation to sustainable reference values.

This research aims at composing energy system designs at the neighbourhood level that are 100% renewable and function within a national energy system instead of being energy neutral on its own. For these renewable energy system designs, the environmental impact for relevant sustainability indicators is mapped and compared to sustainable reference values. This is done to see what are trade-offs between the different sustainability indicators for the renewable energy systems, and how the environmental impact compares to the sustainable reference values. These reference values are defined as quantified indicative 'limit' points. This study takes into account a broad set of sustainability indicators instead of solely focussing in GHG emissions. Besides, this study does not only compare the environmental impact of different energy sources to each other, it analyses them in relation to sustainable reference values, to each other and it identifies trade-offs between the different impact categories. It also considers the geographical scale of the impacts and what the results of this all imply for stakeholders that are involved in the transition to renewable energy systems.

In a case study, renewable designs are made for the energy system of the neighbourhood 'Haven-Stad' in Amsterdam which is in transition to become a residential and business area (Gemeente Amsterdam, 2017). For this neighbourhood, the implications of the environmental impact in different categories are explored in relation to reference values. This information could help stakeholders that are involved in the transition to renewable energy systems as it shows the consequences of 100% renewable local energy systems, as well as possibilities that arise. The aim of the research is defined in a research question that has been devised in collaboration with Alliander for whom this study is performed:

What is the environmental impact of 100% renewable energy systems for urban neighbourhoods in relation to sustainable reference values and what does that imply for stakeholders that are involved in the transition to renewable energy systems?

To answer this research question, six sub-questions are composed:

- Which sustainability indicators are relevant in the context of 100% renewable energy systems?
- What are appropriate sustainable reference values for the sustainability indicators that are relevant for 100% renewable energy sources and in what way could they be compared to the impact of urban local energy systems?
- What is the impact of urban local renewable energy systems for the relevant sustainability indicators and what are trade-offs between the impacts for the different indicators?
- Where is the environmental impact of renewable local energy systems located and to what extent is that in the direct vicinity of the energy consumption area?
- What is the effect of a different energy demand (pattern) on the environmental impact of the renewable local energy systems?
- What can be learned from the (relation between the) environmental impacts and the location of it by stakeholders that are involved in the transition to renewable energy?

At first some concepts that are mentioned in the questions need to be defined precisely because they can be interpreted in different ways. These concepts are 'sustainability', 'local' energy system, and the interpretation of a '100% renewable energy system'. These concepts are defined in section 2.1.

To determine and assess the broad environmental impact of local renewable energy systems, a comprehensive set of sustainability indicators is covered in the research which are relevant in the context of energy systems. The environmental impact of the relevant indicators is mapped and analysed in relation to sustainable reference values that are based on global budgets. Besides, the location of the environmental impact is discussed, as well as the implications for stakeholders of the environmental impact of the renewable systems in relation to the sustainable reference values. This shows the social relevance of this research, because it provides information and advices concerning renewable energy systems, that could contribute to counteract the social problem of climate change.

To get a broad view on the impact of 100% renewable energy systems, multiple renewable designs are made for Haven-Stad with different combinations of renewable energy generation, consumption and storage technologies. The designs for Haven-Stad are simulated and analysed using the modelling tool EnergyPLAN that provides an hourly distribution of the performance of each component in the modelled energy system. Based on the output of EnergyPLAN, the impact is mapped for the sustainability indicators that are considered as relevant in the context of renewable energy systems. As there are uncertainties about how the energy demand will look like in size and distribution, the impacts will be mapped for two types of energy demand; one on the basis of the current average energy demand, and one on the basis of a lower energy demand with a share of flexible electricity demand.

In the remainder of this thesis, the important concepts are defined and discussed after which the case study and the methodology of the study are explained. After the methodology, the results are presented and explained. These results are interpreted and placed in the context of literature in the discussion and conclusion where is also reflected on the study itself.

Chapter 2: Explanation of important concepts and the case study

In this chapter, important concepts are defined and the case study for Haven-Stad is explained to clarify what is the intention with the case study and to provide information about the neighbourhood.

2.1 Definition of sustainability and renewable local energy systems

The definition of the concept of sustainability varies considerably when it is used in different disciplines as it is open to multiple interpretations (Sharifi and Murayama, 2015). In general, the definition from the UN World Commission on Environment and Development has been a source of inspiration for most of the definitions and will be used in this study because of the broadness of the definition. They defined it as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). The four main types of sustainability are human-, social-, economic-, and environmental sustainability and this study focusses only on environmental sustainability (Goodland, 2002).

For a sustainable 'local energy system', a description of the ZEN Research centre can be used to clarify what is meant with a sustainable local energy system: "a group of interconnected buildings with distributed energy resources such as solar energy systems, electric vehicles, charging stations and heating systems, located within a confined geographical area and with a well-defined physical boundary to the electric and thermal grids. The neighbourhood is not seen as a self-contained entity, but is connected to the surrounding mobility and energy infrastructure, and will be optimized in relation to larger city and community structures" (Wiik et al., 2018). The boundaries of Haven-Stad demarcate the area for which energy need to be supplied while the energy system is considered as a part of a 100% renewable national energy system. All demanded energy is produced and consumed within the borders of the country and generated by renewable sources at every moment throughout the year. This means that no import and/or export of energy is incorporated from/to other countries.

2.2 Haven-Stad as case study

In this section a short description of the Haven-Stad neighbourhood is provided as it is important to indicate what the aim is of the case study and in what way the researched area will be examined.

This neighbourhood is assigned by the municipality of Amsterdam as transition area from industry to a residential and business area to counteract the housing shortage in Amsterdam. There is a plan to make this transition in the coming decades to realise around 70000 new houses and 58000 new jobs (Gemeente Amsterdam, 2017). The neighbourhood is intended to become a residential area without industrial activity. This neighbourhood in transition is used for this study to design a sustainable energy system for, without taking into account the current plans for the neighbourhood. This is because it is not intended to give an advice for how to design this specific neighbourhood in the coming years, but more to compose long term renewable designs to see what are the implications for the involved stakeholders of the broad environmental impact of the designs. With the designs, there is only focussed on the energy system components of heating, electricity and mobility within the neighbourhood. It is not intended to strive for a life cycle zero-emission neighbourhood since emissions related to building materials and other objects in the neighbourhood are left out of the scope. It only entails the energy demand and supply for the use phase of the built environment. Mobility elements like EVs are included as these provide electricity demand in the neighbourhood itself.

It is not intended to optimise one energy systems that is the best suitable for Haven-Stad specifically. Haven-Stad is used only as a case study area to see what is the effect of various renewable energy system designs on relevant sustainability indicators and what could be learned from that. The designs are composed with a specific focus to see what is the effect that particular focus. None of the designs are composed with the intension to be a suitable design for local energy systems as the best suitable design is probably somewhere in between the designs.

Chapter 3: Methodology

In this chapter is elaborated on the method to answer the different sub-questions and how this contributes to answer the main research question. At first a short research outline in provided to show an overview of the whole process. After that, for each individual step is explained how it is done, what (type of) data is necessary and why this step is relevant for answering the research question(s).

3.1 Research outline

In order to find out what could be learned from the broad environmental impact of various renewable energy system designs in relation to sustainable reference values, several steps are carried out. At first, the sustainability indicators are analysed to see which are relevant in the context in 100% renewable energy systems. For the relevant indicators, there is elaborated on the sustainable reference values such as the global carbon budget to stay below 1.5 °C and how these budgets can be interpreted and compared to the impact of renewable energy systems. After the relevant sustainability indicators and corresponding sustainable reference values are identified, the various compositions of the energy system designs are determined, followed by a calculation of the energy demand in Haven-Stad. Then, the energy supply in the designs is worked out and simulated in EnergyPLAN to see exactly in what proportion the various components contribute to the energy system. After that, information from the output document of EnergyPLAN is used to map the impacts for the sustainability indicators that are considered as relevant. The impact of the designs are discussed in relation to the sustainable reference values and trade-offs between different impact categories are identified. then, implications for stakeholders that are involved in the transition to renewable energy systems are derived from the results. Lesson that could be learned are sought in the magnitude of the impacts, the trade-offs between impacts for different sustainability indicators, the location/concentration of the impact, and the potential positive effect of a lower and flexible energy demand.

3.2 Selection of sustainability indicators

Environmental sustainability should be analysed in the context of energy systems within this research. Because in many articles and other data sources, the concept of sustainability is applied in a broader context, the relevant indicators should be distinguished from the irrelevant ones. To identify a comprehensive set of sustainability indicators that cover environmental sustainability in the context of energy systems, both scientific and grey literature is analysed. Because the aim of this study is assess the sustainability in a broad sense, there has been looked first at sustainability indicators without focussing on local energy systems.

According to Goodland (2002), environmental sustainability is about protecting natural capital that consists of water, land, air, minerals, and ecosystem services. Environmental sustainability means that humanity has to live the limitation of the biophysical environment and that natural capital must be maintained as a provider of inputs, as well as a sink of wastes. The waste emissions should be kept within assimilative capacity of the environment without impairing it (Goodland, 2002).

The concept of living with the limitations of the biophysical environment is also coming back in the planetary boundary framework. In this framework, nine processes are involved caused by human perturbation that could damage the earth system (Steffen et al., 2015). The processes that are relevant in the context of energy systems are climate change, biogeochemical flows, ocean acidification, land use, fresh water use, ozone depletion, atmospheric aerosols, and chemical pollution. These processes could potentially be caused by the development or operations of energy systems in a direct or indirect way.

The sustainability indicators above correspond largely to the indicators used in scientific articles that are focussed specifically on the sustainability assessment of energy systems. In the overview in table 1, the environmental sustainability indicators are shown that are used in different scientific articles focussed on energy systems, as well as the indicators of articles about sustainability in general. The indicators are named in slightly different ways in the articles but the indicators that are present in almost all studies are ‘global warming’ (GHG emissions), ‘ozone depletion’, ‘freshwater use’, ‘water quality/toxicity’, ‘terrestrial quality/toxicity’, ‘air quality/toxicity’, ‘rational use of resources/materials’, and ‘land use’.

Table 1 - overview of environmental sustainability indicators per study/framework.

	Scientific studies focussed on energy systems										Sustainability in general	
	Gujba et al. (2011)	La Rovere et al. (2010)	Onat and Bayer (2012)	Schenler et al. (2009)	Roth et al. (2009)	Stamford & Azapagic (2012)	Kowalski et al. (2009)	Jacobson (2009)	Evans et al. (2009)	SantOyo-Castelazo & Azapagic (2014)	Planetary boundaries[1]	UN sustainable development goals[2]
Global warming (GHG emissions)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Acidification (emission of SO_2, NO_X, HCl, NH_3)	✓	✓			✓	✓				✓	✓	✓
Eutrophication (emission of N, NO_X, NH_4, PO_4)	✓				✓	✓				✓		
Photochemical smog (VOCs and NO_X)	✓	✓				✓				✓		✓
Ozone depletion	✓					✓				✓	✓	
Air quality		✓		✓	✓		✓				✓	✓
Freshwater use and effect on quality	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Marine water toxicity	✓			✓	✓	✓	✓			✓	✓	✓
Terrestrial toxicity	✓			✓	✓	✓				✓	✓	✓
Availability of (energy) resources, resource depletion	✓		✓	✓	✓		✓	✓	✓	✓		✓
Efficiency of energy generation			✓						✓			
Material recyclability						✓	✓					✓
Land use (occupied area, area made unavailable due to energy generation)		✓	✓	✓	✓	✓		✓	✓		✓	✓
Human toxicity	✓									✓		✓
Thermal pollution								✓				
Effects on wildlife, biodiversity				✓				✓			✓	
Radioactive and non-radioactive waste management				✓				✓				✓

As the environmental sustainability indicators are generally used in LCAs and studies to compare energy systems and supply options where fossil fuels are involved, it could be possible that some of the indicators are not relevant anymore within a 100% renewable system since the exclusion of fossil fuels will solve the negative impacts of the particular indicators. In the section below, this will be discussed.

---

[1] Steffen et al., 2015

[2] United Nations, 2015

3.3 Relevant sustainability indicators in the context of 100% renewable energy systems

Currently, the global electricity production originates for around 75% from fossil fuels and 16% can be attributed to hydropower (IEA, 2019). In the Netherland the non-renewable energy share was even 92.6% in 2018 (CBS, 2019a).The starting point of this study is a 100% renewable national energy system. 100% renewable implies by definition the exclusion of fossil fuels. The exclusion of fossil fuels and exclusive use of low-carbon energy supply options goes along with co-benefits and trade-offs with other environmental impacts (Gibon et al., 2017; Henry et al., 2018; Hertwich et al., 2015; Kouloumpis et al., 2015).

Decarbonization of energy generation has co-benefits in nearly all other environmental impact categories. A decarbonized energy system with 100% renewable sources leads also to a significant reduction of the impact of particulate matter, freshwater eco-toxicity, eutrophication and acidification (Gibon et al., 2017; Hertwich et al., 2015; Kouloumpis et al., 2015). The effect of low-carbon energy supply on photochemical oxidation and ozone depletion depends on the increasing energy demand (Kouloumpis et al., 2015) while material requirements and depletion of (metal) elements will increase significantly in a 100% renewable energy system (Gibon et al., 2017; Hertwich et al., 2015; Kouloumpis et al., 2015). Besides material requirements and element depletion, also land use is a sustainability indicator that will have higher impact for a renewable energy system than for the current system (Gibon et al., 2017; Henry et al., 2018).

Therefore the sustainability indicators of ‘land use’ and ‘the use of critical resources’ are considered as the most important sustainability assessment indicators for renewable energy systems because these impacts will increase while shifting towards a renewable energy supply. ‘Global warming’ is a relevant indicator as well, because that is a primary reason why the change to renewable energy need to be made. These indicators will be focussed on in the formulation of sustainable reference values and in the environmental impact assessment of the designs. In Appendix A is extensively explained why the remaining indicators are not considered as relevant in the context of 100% renewable energy systems, and why they are not considered in the remainder of this research.

3.4 Defining reference values

In current and previous studies in which these kind of indicators are used, the main purpose was to apply them on energy production technologies to see how they compare to each other and to see what the best option is for that particular indicator. What is often neglected is what the value for the indicators means. A sustainable reference value is often not considered and therefore the values of the indicators are not interpreted, only compared. It could be possible that even the worst option can be considered as sustainable, or that all options will cause problems. To cover this, these reference values concerning sustainability will be defined.

For the indicators that are considered relevant and potentially problematic in 100% renewable energy systems (GHG emissions, land use and the use of critical resource), sustainable reference values are defined in the result section. These sustainable reference values are not pretended to be exact values that define the boundary between sustainable and unsustainable. This debatable boundary cannot be defined because of many uncertainties. The limit values are intended to give guidance in assessing the renewable energy system designs and provide an indication to compare the impact of the designs with, to put it into perspective. Reference values can be based on for example the carbon budget for 1.5 °C temperature increase, maximum available land, global reserves of critical elements, etcetera. This is important for answering the research question as it shows how the different designs compare to the reference values and on what points bottlenecks will occur. That can show what parts of the design cause problems and it gives possibilities to interpret the results to argue to what extent the impact of a particular design contribute to the indication for maximum impact. Another important lesson that could be learned from these results is how the impact of the designs on different sustainability indicators relate to each other and to what extent they overlap and contradict.

The sustainable reference values are based on sources that are widely accepted as sustainable and articulated in formal documents like frameworks, articles or agreements. Examples of the sources are the planetary boundary framework or the global carbon budget to stay below 1.5 °C temperature increase. These values are helpful for assessing renewable energy systems by providing an argued indicative sustainable limit.

3.4.1 Allocation of global sustainable reference values

Environmental impact and sustainability targets are often defined as a global resource budget (e.g. maximum amount of GHG emissions or available land). Because of a globalized economy, the impact of (energy related) activities is not only present in the area where the energy is consumed, but along the whole production chain. To translate the global budgets into national or local budgets/targets, there are multiple options to allocate the available resources. The global budgets could be downscaled to smaller regions or a budget per capita, on the basis on the different principles that are explained below (Lucas and Wilting, 2018). None of these methods are inherently good, and they are not arranged in a specific order.

- A possible way of allocation is ‘grandfathering’. This is based on the idea that the current resource use constitutes a ‘status quo right’. The global budget is allocated based on a countries current share in the global environmental pressure or impact.
- Another way is ‘equal per capita’ allocation. With this principle the global budget is allocated on the basis of a region’s share in the global population. A variant on this is the idea of ‘equal cumulative per capita’ allocation. This works the same but with cumulative population numbers.
- The third option is to allocate the global budget on the basis of the ‘ability to pay’. With this principle, the allocation is based on the GDP of a region in relation to other countries. The regions with the highest capacity to pay contribute to a larger extent to the necessary mitigation.
- The last option is based on ‘development rights’. This method allocates GHG emissions based on quantified capacity (GDP per capita and income distribution) and responsibility (contribution to climate change).

For GHG emission, land use and the use of critical resources, a global budget is defined that is translated to a budget per year per capita using one or more of the above mentioned approaches. These budgets per capita will be used as sustainable reference values to compare the impact of the energy system designs for Haven-Stad to, with the aim to assess them in the light of a broad definition of sustainability. This gives room to analyse the environmental impact of the energy systems of Haven-Stad in a qualitative way, from different points of view.

3.5 Composition of the energy system designs

As multiple compositions of potential components of energy systems could built up to a 100% renewable scenario, several designs are made for Haven-Stad. The first step to compose the designs is to identify the components out of which the designs could be built while, taking into account the starting point of 100% renewable energy supply. Within the EnergyPLAN model, a comprehensive set of energy supply and storage technologies is included. By excluding the technologies that are out of the research scope, that are associated with emissions, or do not meet the definition of sustainability, the technologies in the table below are considered as potential components of a sustainable energy system. The table shows only the different technologies for heat, electricity and storage. There are other input data and setting required in EnergyPLAN that are not relevant to show in this chapter. The full set of input data and setting that used in EnergyPLAN can be found in Appendix C.

Table 2 - Overview of all potential components of the energy systems, included in the EnergyPLAN model (Lund and Thellufsen, 2019).

Power generation	**Heat production (IHH)***	**Heat production (DH)***	**Electricity storage**	**Heat storage**
Photovoltaic (PV)	Solar thermal	Solar thermal	Compressed air electricity storage	No specified techniques
Wind power	Electric heating	Industrial waste heat	Battery storage	
Geothermal power	H_2 micro CHP	Boilers	hydrogen FC storage	
Concentrated solar power (CSP)	Biomass micro CHP	CHP plants	Electric cars (V2G)	
Biomass/H_2 Micro CHP	Biomass boilers	Heat pumps		
Biomass/H_2 CHP	Heat pumps	Electric boilers		
Power plant		Geothermal		

*IHH = individual house heating, DH = district heating

The alternative technologies in table 2 are used to compose different energy system designs for Haven-Stad. Based on different options for energy systems and the considered sustainability indicators, different energy systems are composed with different focusses. The different design are found in the extremes of common approaches and the sustainability indicator. This is done so it becomes clear what components cause certain effects, which is better visible if the different designs represents the extremes in different categories. Below, a short description of the different composed designs is provided, as well as a graphical overview of the designs.

3.5.1 Reference design

This design is a simplified version of the current energy supply system in the Netherlands. All heat is provided by individual house heating using natural gas boilers. Electricity comes for the largest share from power plants with a fuel distribution as in the national electricity mix. The renewable share in the electricity production is also calculated on the basis of the Dutch electricity mix. Shares are derived from CBS (2019b). The 'overige' renewable electricity production is divided over wind and solar PV.

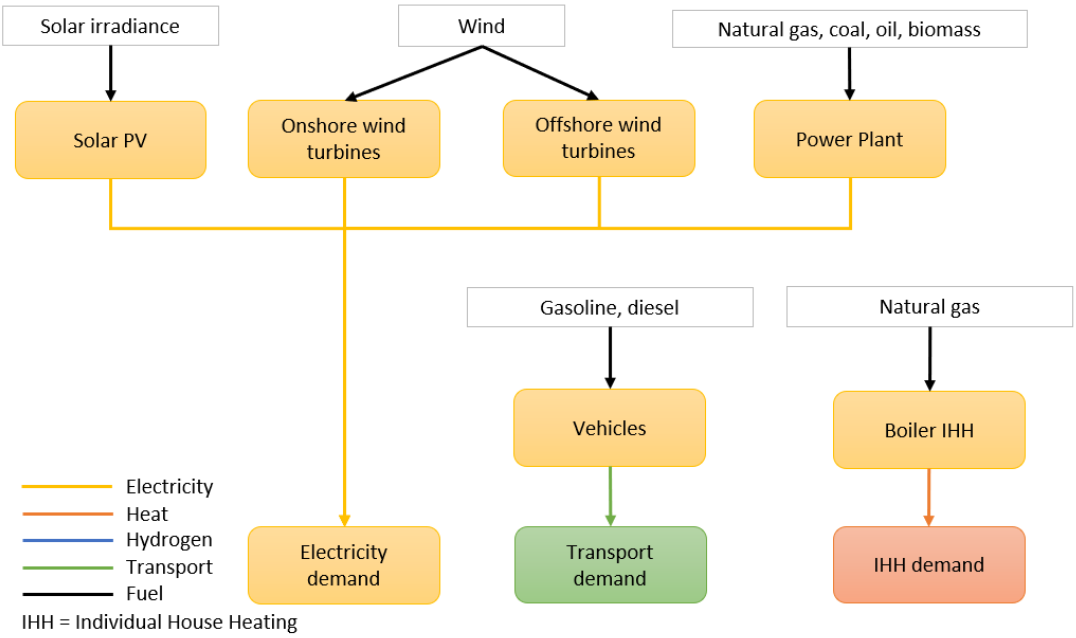


Figure 1 - Schematic overview of the reference design

3.5.2 All-electric design

In this design, all energy is provided by electricity. Electricity is generally from solar PV, onshore- and offshore wind with a biomass power plant to cover the demand in the hours that the intermittent sources are not sufficient. Battery energy storage for electricity storage. The heat is provided by IHH heat pumps and transport is provided by electric vehicles.

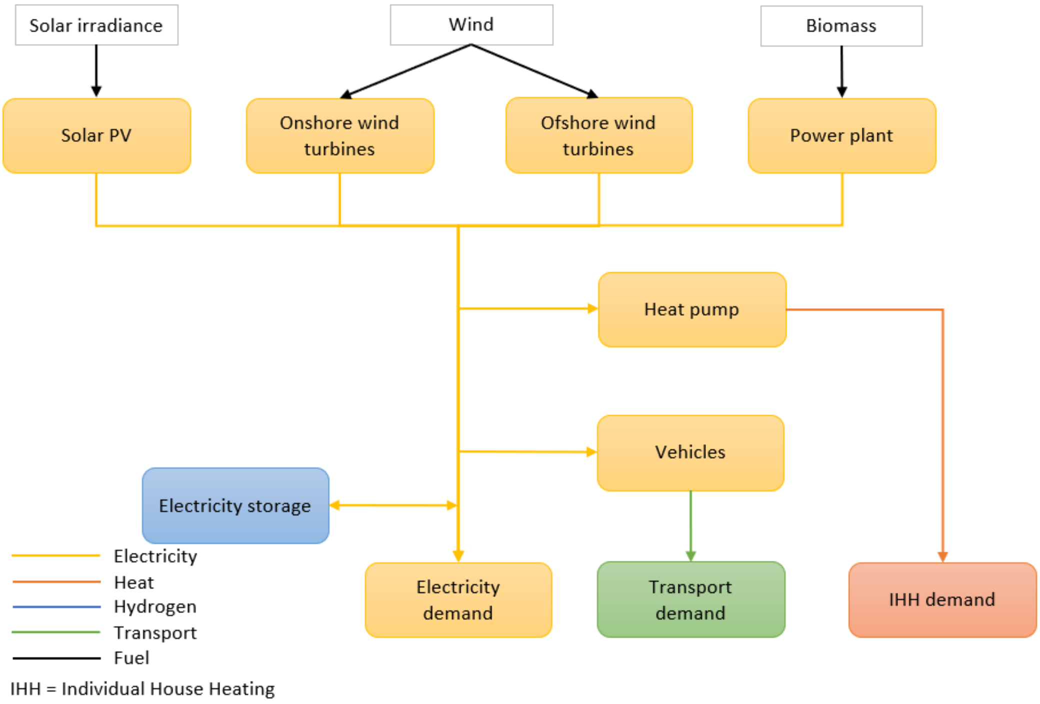


Figure 2 - Schematic overview of the all-electric design

3.5.3 Minimum land use design

IHH is provided by heat pumps in combination with (IHH) solar thermal. The DH consists of geothermal and solar thermal in combination with a hydrogen boiler/CHP and electric heating to manage excess electricity production. Electricity is provided by wind and solar PV. In this design no biomass is incorporated to minimize the land requirement. Biomass has the highest land use intensity of all energy sources. The design incorporates battery electricity storage and electric vehicles.

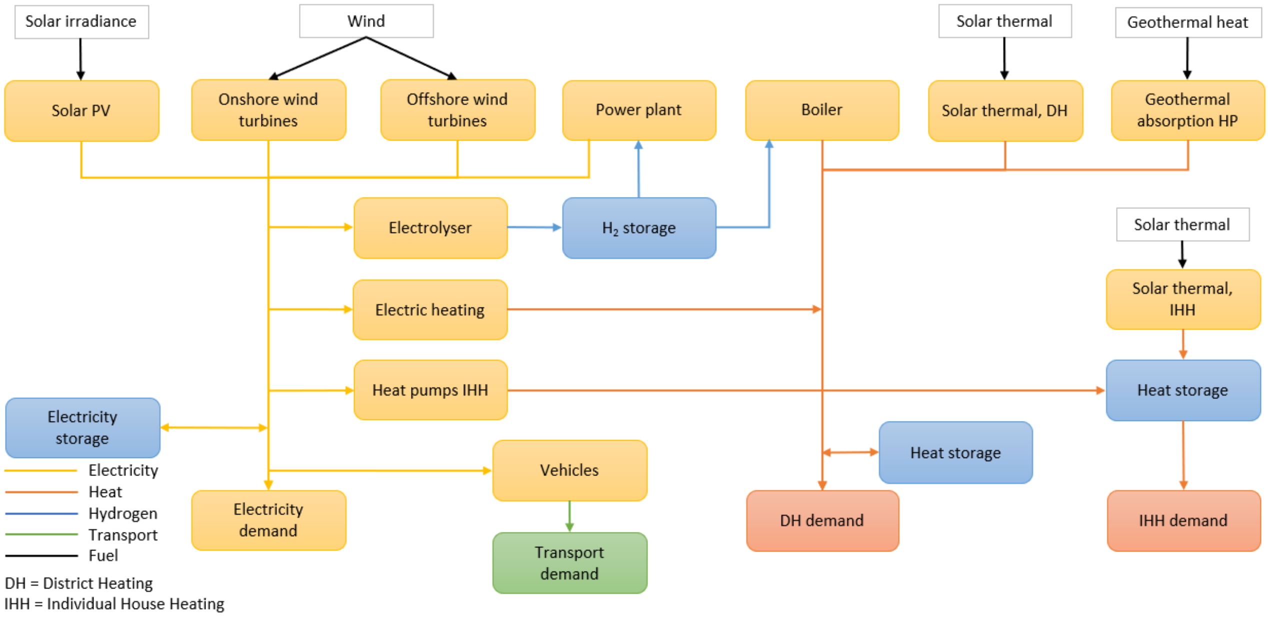


Figure 3 - Schematic overview of the minimum land use design

3.5.4 Low critical resources design

This design is composed with a small share of wind and solar PV and no batteries as these are primarily responsible for the use of critical resources. A design could be made without solar PV and wind but on beforehand can be known that this would require an unrealistic high amount biomass. In this design electricity is provided by wind turbines, solar PV and a biomass CHP that can function as power plant when required. The required heat comes from (IHH and DH) heat pumps, geothermal, solar thermal, biomass boiler and electric heating. Transport is provided by electric vehicles.

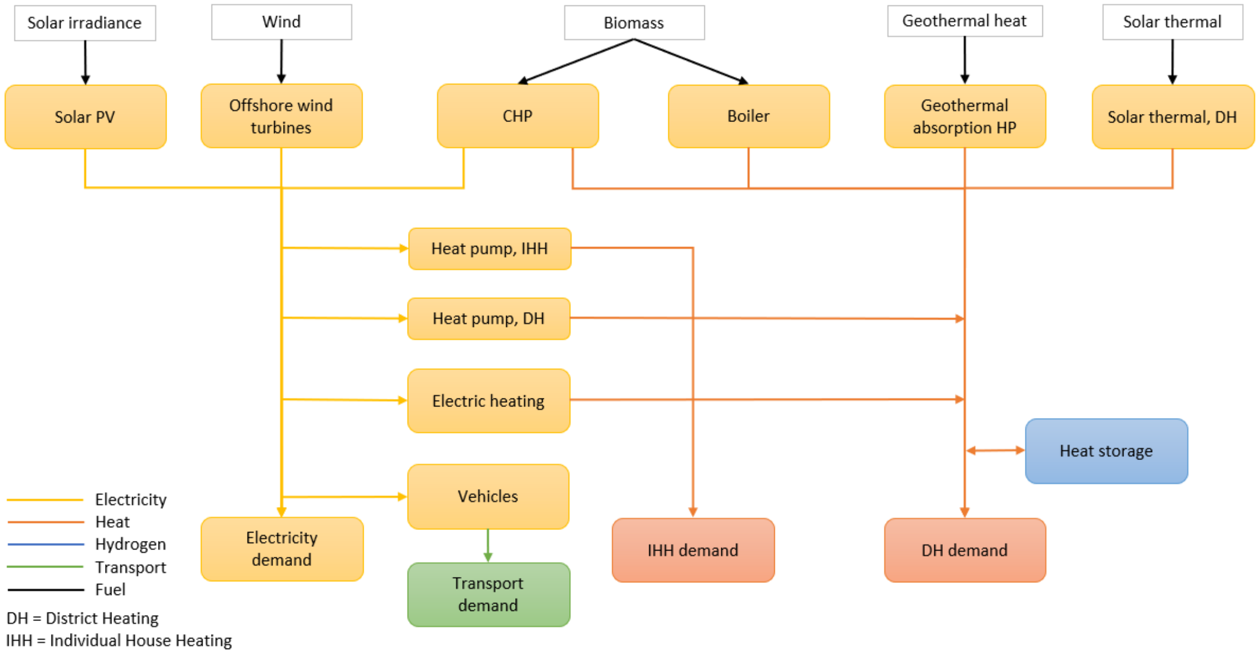


Figure 4 - Schematic overview of the low critical resources design

3.5.5 Central production design

In this design no individual house heating is applied. Heat is supplied via central production and a district heating network. The heat originates from a biomass CHP, solar thermal, heat pumps and electric heating while an electrolyser is used as a solution for hours with excess electricity production. The produced hydrogen is used to fuel cars and to fuel the CHP and boilers for district heating. Electricity is supplied via a central system as well. This is done by onshore wind, offshore wind, biomass CHP and small amounts of PV as this design only allows only central production.

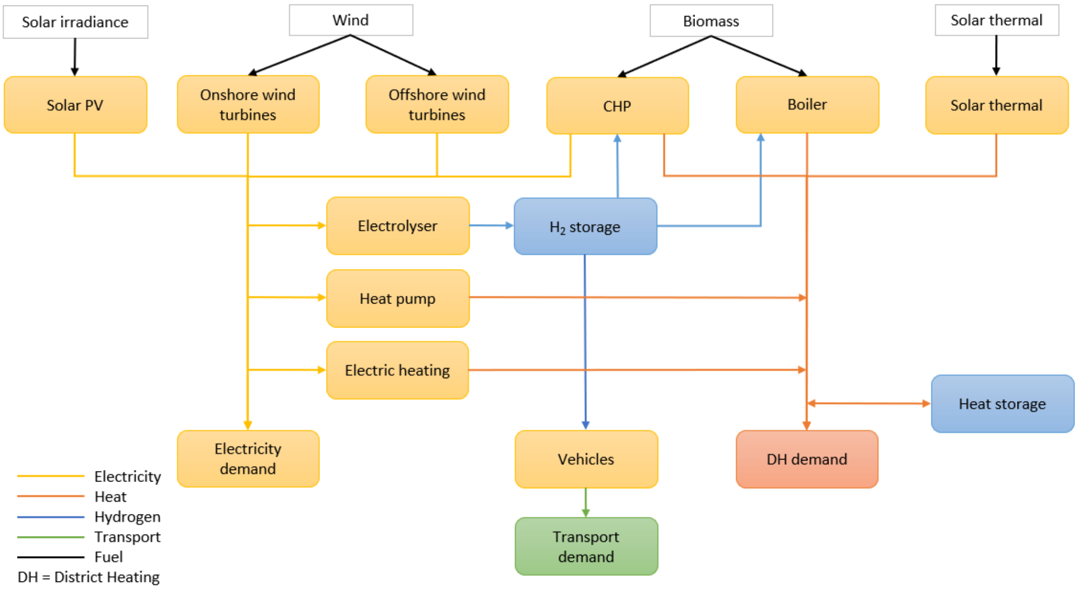


Figure 5 - Schematic overview of the central design

3.5.6 Biomass design

In this design, bioenergy is used to provide for the majority of the energy demand. As biomass goes along with the possibility to implement BECCS, there is a possibility to reduce the GHG emission to negative values. This design is developed to see what is possible and to what extent the emissions could be reduced, in contrast to the other designs. Also the effect of a high share of biomass on the other sustainability indicators is interesting to see. A small share of solar PV and onshore wind are incorporated, but the majority is generated by biomass. Biomass has the advantage that it is not an intermittent sources so no or little energy storage is required.

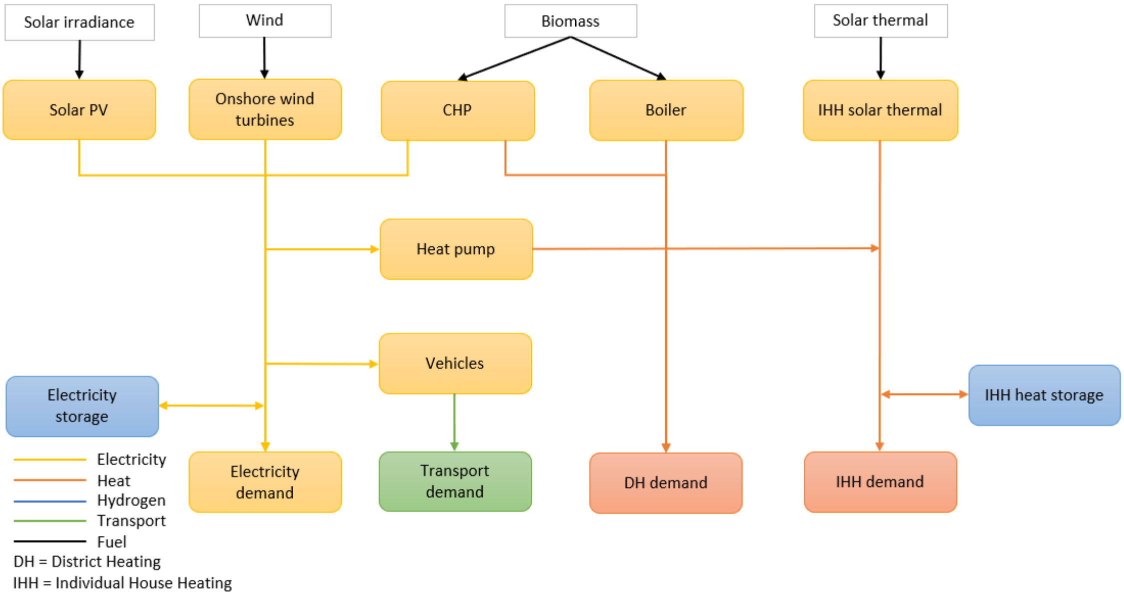


Figure 6 - Schematic overview of the biomass design

3.6 Simulation model selection

The Haven-Stad neighbourhood is not built yet and there is no data available that can be used to prove how the above explained energy systems will function. To make a coherent technical analysis of the neighbourhood's energy system, computer modelling tools are required to simulate the systems. As there are many tools, which are focussed on different types of energy systems, it is a challenge to find the best suitable tool for this study. Therefore the article of Connolly et al. (2010) proposes a number of categories and characteristics to assess different tools. They reviewed 37 tools for analysing the integration of renewable energy into energy systems. The parameters that were discussed in the review help to select an appropriate simulation model.

By applying these parameters to the case study in this research, an appropriate model for this study could be assigned. As the aim is to design a sustainable energy system, the tool should be able to simulate a 100% renewable energy system. Besides, the model to use should be able to simulate, take into account different scenarios, perform a bottom-up approach and optimize the operations. The tool should be accessible in the Netherlands and must be able to make analyses on neighbourhood level (regional/local) for at least one year to see whether the system could function throughout the year. As the study focusses on the operational energy use of the buildings in the neighbourhood, the electricity and heat sector should be incorporated as long as it influences the direct energy use within the built environment. So (electric) transport should be incorporated as they contribute directly to the neighbourhood's energy demand.

A tool that meets the requirements above is EnergyPLAN. As negative aspect of EnergyPLAN could be said that the tool is generally used at national/state/region level (Connolly et al., 2010) although examples are available where the model is used to simulate 100% renewable energy systems in cities and (small) islands (e.g. Mathiesen et al., 2015a; Mathiesen et al., 2015b; Child et al., 2017). As the EnergyPLAN model has already been used for cities and for smaller regions with less inhabitants than Haven-Stad, it is plausible to argue that the model could also be used for Haven-Stad.

EnergyPLAN is a computer model that can be used for simulation of the optimal operation of energy systems. It is a deterministic input-output based model for calculating the operations of an energy system in one full year using a time resolution of one hour. It is suitable for this study as the model is designed for integration of renewable energy and for the integration of the electricity-, (district) heating-, and mobility system which makes it possible to simulate 100% renewable energy systems (Lund and Thellufsen, 2019). In Lund and Thellufsen (2019) the full documentation of the model can be found.

3.7 Energy demand in Haven-Stad

To apply the described energy system composition in a worked out design in EnergyPLAN, it is necessary to know the energy demand in Haven-Stad. There are many uncertainties in the future development of components in energy systems that might have significant influence on the outcome and functioning of future energy systems. Most of them result in a different energy demand pattern and total amount of energy demand. The electricity load profiles will change fundamentally in residential areas due to changes in the energy system (Klaassen et al., 2015; Veldman et al., 2013). As the aim of this study is to analyse local energy systems, these potential changes needs to be taken into account, because there are a variety of plausible developments that will result in different demand patterns. These possible developments could be based on social, regulatory, and technological sources.

Because of these kind of uncertainties, the renewable designs are modelled with two different energy demands. The first is based on the current energy average demand per household and utility building in Amsterdam, and the second energy demand is based on well isolated newly constructed buildings with a share of flexible electricity demand of 10%. The exact calculation and explanations of the energy demand can be found in Appendix B. For both the energy demands the environmental impacts for GHG emissions, land use and use of critical resources is calculated and analysed. In this way a sensitivity in the results, caused by uncertainties, is incorporated what gives an extra dimension in assessing the outcomes. The table below shows the energy demand for Haven-Stad for the two considered types of energy demand. For the demands an expected population of around 120000 is assumed for Haven-Stad, and around 58000 workplaces, both derived from the development strategy of the municipality (Gemeente Amsterdam, 2017). For all assumption (e.g. for the assumed amount of cars) and calculation, see Appendix B.

Table 3 - Expected energy demand for households and utility buildings in Haven-Stad on the basis of current average energy demand in Amsterdam and low/flexible energy demand.

	Heat demand	Electricity demand	**Total**
Current average energy demand (PJ/yr)	2.94	0.93	**3.87**
Low/flexible energy demand (PJ/yr)	2.57	0.93 (of which 0.093 flexible)	**3.50**

3.8 Energy supply Haven-Stad

To match the energy demand defined in the previous section, the energy supply in each design is worked out specifically, so it could be modelled in EnergyPLAN. The composition of the designs is explained in section 3.5. For the different components of the designs, a balance is found so that the energy system could function properly. All detailed specifications of each design and input values for EnergyPLAN can be found in Appendix C. This includes the size, capacities, efficiencies of energy production, conversion, consumption and storage technologies, as well as simulation strategy and how to manage excess electricity. In this section the relevant information about the designs is provided, just as important outcome of the simulation in EnergyPLAN. The EnergyPLAN output of the designs is used to calculate the environmental impacts for the relevant sustainability indictors.

To clarify the composition of the designs and to what extent each energy source contribute to the energy supply, the primary energy use for each design is shown in figure 7. It entails the full energy use for the neighbourhood, including electricity, heat and car transport. It shows that all renewable designs have a lower primary energy use than in the reference design. This is because in the reference design, the energy is predominantly generated by fossil fuels that have a conversion loss from primary energy to end use energy. For solar PV and wind, the primary energy shown in the figure represents the energy that is produced by PV and wind turbines. The all-electric design has a significantly lower primary energy use than the remaining renewable designs due to the fact that all heat is produced by heat pumps which produce more heat than the required electricity input. The share of heat pumps in the other designs where heat pumps are included is lower. For the central design was expected that the primary energy use was higher because this design has a share of hydrogen that is produced and used what goes along with conversion losses. But due to the relative high share of heat pumps, the primary energy use had decreased again. In Appendix C, a table is provided with the primary energy use for each energy source per design, as well as the potential energy could be produced wind the installed capacity of wind and solar PV.

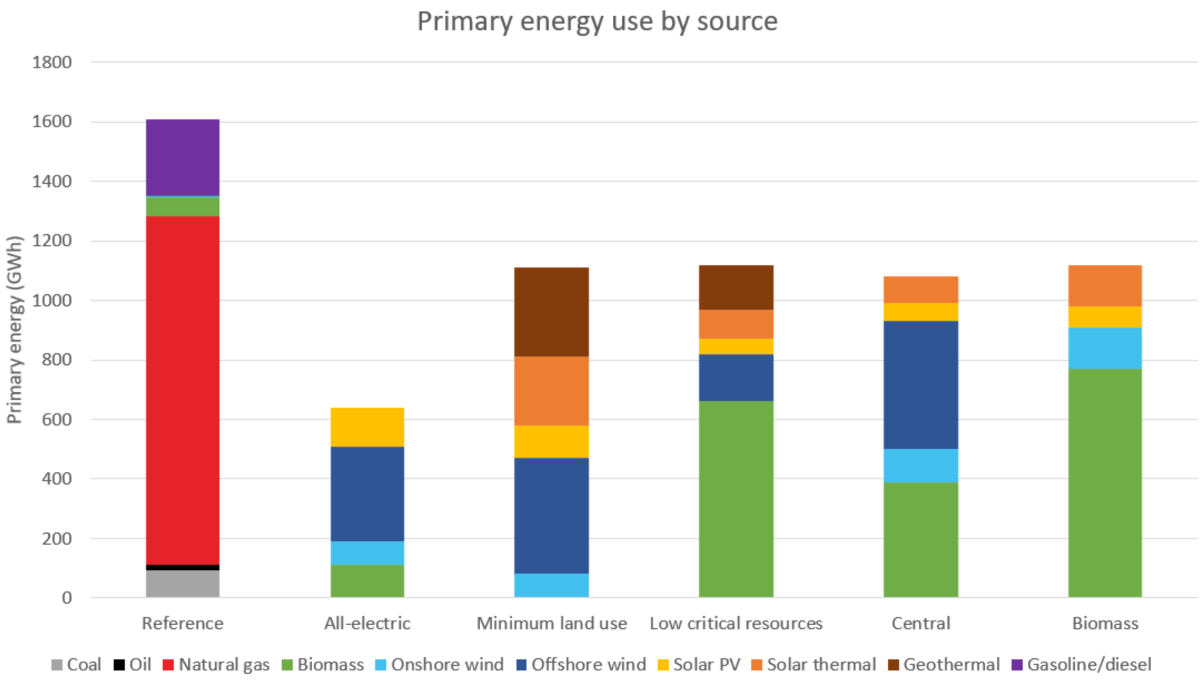


Figure 7 - Overview of the primary energy use in each design for electricity, heat and car transport in Haven-Stad. For low/flexible demand only as the figure with current average energy demand shows a similar distribution in slightly higher amounts.

3.8.1 Installed capacities

For the energy supply in Haven-Stad, the energy is generated by energy production and storage technologies that have a production or storage capacity. For these technologies, the capacities in the designs are shown in the table below, for the ‘current average energy demand’ and the ‘low/flexible demand’. These are the values that are put into EnegyPLAN, in which only the energy supply for Haven-Stad is modelled and not for other regions. Since Haven-Stad’s energy system is not autonomous and part of a larger energy system, it is not the case that there are a set of specific wind turbines and PV panels that are placed specifically for Haven-Stad but a share of the total capacity can be assigned to Haven-Stad. With biomass CHPs, powerplants or large scale boilers, there is not a plant that only provides energy for Haven-Stad. It could be the case that a share of the production of a power plant or CHP is used in the neighbourhood, just as it is at the moment.

Table 4 - The installed capacities of the energy production and storage technologies in the renewable designs. Before the "/ " is with current average energy demand, after for low/flexible energy demand.

	Reference	All-electric	Min. land use	Low critical resources	Central	Biomass
Onshore wind (MW)	1.52 / 1.52	80 / 70	60 / 50	0 / 0	80 / 70	65 / 63
Offshore wind (MW)	0.8 / 0.8	120 / 116	175 / 125	50 / 49	145 / 135	0 / 0
Solar PV (MW)	1.55 / 1.55	120 / 110	100 / 90	40 / 38	50 / 45	65 / 63
Charge/discharge capacity (MW)	0 / 0	90 / 90	90 / 90	0 / 0	0 / 0	90 / 90
Battery (storage capacity GWh)	0 / 0	3 / 2.5	3 / 2.7	0 / 0	0 / 0	0.5 / 0.3
Electrolyser (MW)	0 / 0	0 / 0	45 / 40	0 / 0	30 / 30	0 / 0
CHP electric capacity (MW)	0 / 0	0 / 0	0 / 0	75 / 75	56 / 56	75 / 75
CHP thermal capacity (MW)	0 / 0	0 / 0	0 / 0	150 / 150	157 / 157	150 / 150
PP (MW)	48 / 48	101 / 97	67 / 65	75 / 75	65 / 65	75 / 75
DH Boiler (MJ/s)	0 / 0	0 / 0	115 / 115	70 / 70	110 / 120	123 / 123

3.9 (Location of the) Impact of local energy system and implications for stakeholders

A local energy system has negative impacts on sustainability in different categories for which sustainability reference values are formulated. To map the impact of the different designs, the earlier described designs are modelled and simulated in EnergyPLAN. EnergyPLAN produces an output document that includes all energy (hourly) demand profiles and energy production and storage capacities (per hour) for a full year (output documents are shown in Appendix C). All activities, fuel use, storage, capacities, efficiencies, etcetera, are provided from which the impacts for the sustainability indicators can be derived. For each of the considered indicators (GHG emissions, land use and use of critical resources), the impact of the designs is calculated and worked out in Excel. This is done using the output of EnergyPLAN and data that is derived from literature. The required data are the lifecycle GHG emission intensity of the components in the energy systems, as well as their land use intensity and material use intensity of critical metals. Calculations and further explanation on the environmental impacts of the designs can be found in the result section and Appendix C and D.

Besides the overall impact, the source and location of the impact is necessary to know to answer the research question(s). It is important to know how the impact is geographically distributed because that could be relevant for involved stakeholders to base their decision on. It is important to know if the use a particular energy source has environmental impact within the country where the energy is used, or at the location where for example the required elements are extracted. Therefore, in the analysis of the impact for each sustainability indicator, the area where the impact occurs is considered. As Haven-Stad is not seen as an energy autonomy, the scale from where energy of resources can be imported need to be considered and taken into account in the analysis. In the results section is per type of energy source for each sustainability indicator explained what is the assumed scale from which energy, fuel or materials can be imported and where the impact will take place. The environmental impact of a region has to be determined by what it consumes instead of what it produces to determine the total impact (Lucas and Wilting, 2018). Most of the environmental footprints within the Netherlands remained constant since 1995, while the share of environmental impact abroad increases. This indicates an externalization of environmental pressures and impact (Lucas and Wilting, 2018).

Not only the environmental impact of the energy supply system is important, also the role of the energy system in the larger, national system, is important. This includes how the local energy system compares to the national system, and what is the impact of (potential) import/export of electricity or heat between regions within the country. How deviates the energy system of an urban neighbourhood from a rural area, and in what way are they complementary to each other. This will be taken into account in the discussion to interpret in a qualitative way what results are specific for urban neighbourhoods and what that implies on national scale. Impacts of local energy systems could deviate from each other as it is commonly known that there is not one ideal energy system, but the ideal overall energy system is an assembly of complementary local systems that are adapted to their own circumstances. This idea helps to discuss the environmental impact of the different designs, and argue in what ways the designs for Haven-Stad could be useful to achieve a 100% renewable energy system in the Netherland.

From all results on the environmental impact of the renewable designs, lessons could be learned for stakeholders that are involved in the transition to renewable energy systems like municipalities, national government, architects and real estate developers. Lessons that could be learned are sought in the size of the impacts, the trade-offs between impacts in different sustainable indicators, location/concentration of the impact, and the potential positive effect of a lower and flexible energy demand. Stakeholders could make argued consideration based on the gained information about the (relation between) impacts as they could be attributed to particular (compositions of) energy sources and technologies. The reference values that are derived from global budgets and the different allocation approaches can give guidelines, boundaries, and possibilities for actions to take regarding policy making and implementing energy systems in neighbourhoods. This will be discussed in the discussion in which specific conclusions can be found.

3.10 Data requirement and collection for input EnergyPLAN model

To compose the energy system designs and to simulate them in EnergyPLAN, the specifications of all demand and supply aspects need to be analysed and put into EnergyPLAN. There is a lot required input data and settings for the EnergyPLAN model regarding demand, supply, storage & balancing, and simulation. The required input data and settings that are necessary and has an effect on the outcome of the simulation can be found in the documentation of EnergyPLAN (Lund and Thellufsen, 2019). The input data that was necessary to model the designs and has affected the outcomes where the environmental impacts are based on, are shown in Appendix C. This entails the efficiencies, capacities, storage capacities, hourly distributions, excess electricity strategy, simulation strategy etcetera. Also the data sources are shown from which the information and hourly distributions are derived.

Chapter 4: Results

In the methodology chapter and Appendix A is explained which of the sustainability indicators are considered as relevant for this study and which are not. For the sustainability indicators that are assumed to be relevant (GHG emissions, land use and the use of critical resources), sustainable reference values are defined and discussed in this chapter. After the explanation of how the environmental impact for these indicators could be compared to the reference values, the actual impact of the designs is mapped, shown and discussed. The sustainable reference values are used to compare the environmental impact of the designs to, to give guidance in the environmental impact assessment of the designs. This is done in a qualitative way without labelling the designs as sustainable or unsustainable, but to see what the implications are of the distance to the indicative limit values. The remarkable results are explained and implications of the results are presented.

4.1 Sustainable reference values global warming

The anthropogenic GHG emissions contributing the most to global warming by means of radiative forcing are CO_2, CH_4, halocarbons and N_2O of which CO_2 is by far the major contributor (Dones et al., 2004). Each GHG contributes in varying degrees to global warming per kg and this is measured in Global Warming Potential (GWP), what is expressed in kg CO_2-equivalent (Kim et al., 2014). The concentration of GHGs in the atmosphere is the determining factor in global warming so a maximum amount of GHG emissions has been defined as a reference value to compare the impact of Haven-Stad to. A generally used reference value is the global carbon budget of 400 Gt CO_2-eq. that correspond to the target of a limited global temperature increase of 1.5 °C above pre-industrial levels (Lucas and Wilting, 2018).

To achieve the target of preventing the carbon budget from being exceeded, the global budget can be allocated to regions in different ways, resulting in different budgets per capita in each region. In section 3.4.1, the four approaches are explained to allocate the global budget to a smaller scale. In Lucas and Wilting (2018), these four options are applied to allocate a share of the global carbon budget to the Netherland. In the table below, the carbon budget per person per year is shown on the basis of four different approaches to allocate a share to the Netherlands. For the values, a global carbon budget of 400 Gt CO_2-eq. is assumed that correspond to the target of a temperature increase of 1.5 °C (Lucas and Wilting, 2018). A significant decrease in GHG emissions need to be realised as the current global emissions are 36 Gt CO_2-eq. per year of which 21.28 Gt is caused by the 'electricity & heat' and 'manufacturing energy' sector combined (Ritchie and Roser, 2020). The current consumption based GHG emissions in the Netherlands are shown as well, just as the global emissions per capita to see the required reduction. These numbers are the total emission per person, so not yet specified for energy related emissions. These numbers are used as a sustainable reference to compare the GHG emissions in the renewable design for Haven-Stad with. This provide possibilities to assess the contribution of the energy systems of Haven-Stad to the total carbon budget per person in a qualitative way, from different points of view.

Table 5 - The current average emissions in the Netherlands and globally, and the allocation results of the global carbon budget to the Netherlands for the 5 approaches (Lucas and Wilting, 2018)

	Current GHG emissions (tCO_2-eq./cap./yr)
Current average global emissions	4.4
Current emissions NL	12.5
	Carbon budget (tCO_2/cap./yr)
Grandfathering	1.9
Equal per capita	0.7
Cum. equal per capita	0.6
Ability to pay	-1.7
Development rights	-6.6

The GHG that is currently emitted, decreases the amount that can be emitted in the future, resulting in a decreasing budget over time. For land use and the use of critical resources, the budget does not change in time. The maximum available land remain constant over the years. Also the used amounts of the resources do not cumulate as they can be re-used or recycled. As the carbon budget changes in time and need to be reduced to zero, the carbon budget that is allocated for the Netherlands is equally spread over the years up to the year 2100 (Lucas and Wilting, 2018). In that way the carbon budget can is defined per person per year.

The values in table 5 correspond to a temperature increase of 1.5 °C, compared to pre-industrial. In the Paris agreement is agreed that the temperature increase need to be limited to a maximum of 2.0 °C and strive for 1.5 °C to keep the consequences of climate change manageable in the future (Klimaatakkoord, 2019). The carbon budget that correspond to 2.0 °C is 840 Gt CO_2-eq. what is more than twice as much as the carbon budget for 1.5 °C (Lucas and Wilting, 2018). In the assessment of the impact of Haven-Stad, the 1.5 °C budget is used as reference but it is important to note that the margin before the 2.0 °C is reached.

4.1.1 Carbon intensity

To contribute to a 100% renewable national energy system, excluding fossil fuels should be sufficient. But as this still leaves room for GHG emission related to the raw material manufacturing and the production of technologies, the carbon footprint of the energy systems is assessed by comparing them to the maximum total GHG emissions described above. As the maximum total GHG emissions are not specified for specific sectors, it is hard to interpret the share of GHG emissions of Haven-Stad to the total emissions. Therefore, also the carbon intensity is considered to give an indication whether the lifecycle GHG emissions per produced unit of energy are below an indicated maximum for energy production.

Currently, the carbon intensity of electricity production systems is relatively high because of the large share of fossil fuels in the electricity mix. Different studies show different values for carbon intensity of electricity production but the carbon intensity in the Netherlands is around 400 to 500 g CO_2-eq. per kWh (Ang and Su, 2016; CBS, 2020a; van Wezel, n.d.) and globally around 500 g CO_2-eq. per kWh (Pehl et al., 2017; Ang and Su, 2016). By excluding fossil fuel based technologies and including solely renewable sources, the carbon intensity will reduce significantly. To come to a well-founded estimate of a sustainable level, scenarios from the IPCC and IEA are consulted which are developed aiming to stay below the 1.5 – 2.0 °C temperature increase. From these scenarios, the carbon intensity of energy production in the year 2050 is taken to compare the carbon intensity for the designs for Haven-Stad to.

In the IPCC 1.5 °C pathways, the carbon intensity of electricity production in 2050 has fallen to -330 to +40 g CO_2-eq. per kWh across the 1.5 °C pathways (Rogelj et al., 2018). A negative carbon intensity can be achieved due to bioenergy with carbon capture and storage (BECCS). The (median) carbon intensity of electricity production for the IPCC AR5 scenarios in line with 2 °C is 15 g CO_2-eq. per kWh and BECCS can achieve net-negative emissions of -312 g CO_2-eq. per kWh (Pehl et al., 2017). The IEA BLUE Map climate change mitigation scenario that is moving toward 2 °C temperature increase mentions carbon intensity of electricity production of around 100 g CO_2-eq. per kWh in 2050 (Hertwich et al., 2015). At last the sustainable development scenario of the IEA include a carbon intensity for electricity of 23 g CO_2 per kWh (IEA, 2019). The average of these carbon intensities, 44.5 g CO_2-eq. per kWh, is used as indicative limit value to which the average carbon intensities of the energy system designs for Haven-Stad will be compared to give an indication whether the carbon intensity is in the same range or not.

In the table below, these carbon intensities are shown as an indication how realistic this carbon intensity is. The relative wide range can be explained by different outcomes of different studies, and the different ways of mapping the carbon intensity (e.g. what type of PV panels, what type of biomass etc.). The carbon intensity of energy generation technologies seem to reduce up to 2050 (Pehl et al., 2017). The carbon intensity of e.g. nuclear, wind and PV and is expected be between 3.5 to 11.5 g CO_2-eq. per kWh in 2050 (Pehl et al., 2017). The table and figure below shows the carbon intensities of different energy supply methods and the average of the IEA and IPCC scenarios.

Table 6 - Carbon intensity of currently available renewable energy generation technologies. Data sources in caption.

Primary energy source	Range carbon intensity (g CO_2-eq./kWh)	Median
Coal	871 – 1440 [1, 4, 5, 6, 8, 9, 10, 12]	1012
Oil	815 – 900 [4, 8, 10, 12]	859
Natural gas, power	431 – 620 [1, 4, 5, 6, 8, 9, 10, 12]	529
Natural gas, heat	210 – 380 [13]	295
Nuclear	8 – 63 [1, 4, 8, 9, 10, 12]	21.2
Hydro	3 – 42 [1, 4, 6, 7, 8, 10, 11, 12]	22.2
Wind	6.3 – 25 [1, 3, 4, 5, 6, 7. 8, 9, 10, 11, 12]	12.5
Solar PV[3]	27 – 99 [1, 2, 4, 5, 6, 7, 8, 9 , 10, 11, 12]	66
Solar thermal	21.6 – 72 [8, 11, 13]	22.5
CSP	28 – 32 [1, 4, 5, 7]	30.5
Geothermal, heat	10 – 55.8 [4, 7, 8, 10, 11, 13]	37
Biomass, power	66 – 332 [1, 4, 8, 10, 11]	81
Biomass, heat	27 – 45 [8, 11]	36

Data sources: 1: Gibon et al. (2017); 2: De Wild-Scholten (2013); 3: Wang and Sun (2012); 4: Hydro-Québec (2014); 5: Hertwich et al. (2015); 6: Evans et al. (2009); 7: Asdrubali et al. (2015); 8: Cherubini et al. (2009); 9: Stamford and Azapagic (2012); 10: Singh et al. (2013); 11: Amponsah et al. (2014); 12: Kaldellis and Apostolou (2017); 13: Squires and Goater (2016).

---

[3] Dependent on type and geographical location of production and installation because electricity generation potential varies by local irradiance (Kim et al., 2014; de Wild-Scholten, 2013).

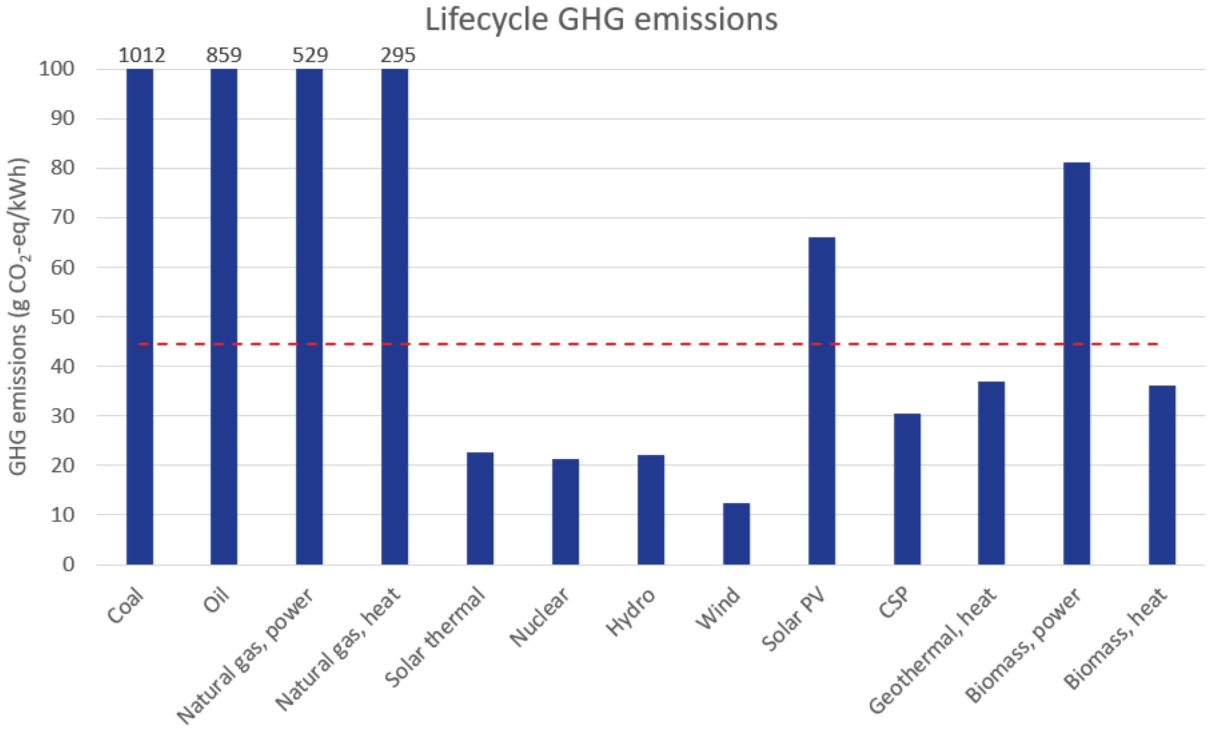


Figure 8 - Lifecycle GHG emission of energy production from different energy sources.

4.2 GHG emission impact of the energy system designs for Haven-Stad

The lifecycle GHG emissions of each design are shown in figure 9, presented in t CO_2-eq./cap./year. In this unit, it can be compared to the carbon budget as explained earlier in section 4.1. The carbon budget is allocated according to the different principles and presented as horizontal lines. The allocation of the global carbon budget on the basis of 'ability to pay' and 'development rights' are not shown in this figure as these are negative and would make the figure unclear to read. The carbon budget per capita based on 'ability to pay' and 'development rights' are respectively -1.7 and -6.6 t CO_2-eq./cap./year (see table 5). The 'equal per capita' and 'cumulative equal per capita' approaches are used in most planetary boundary translation literature (Lucas and Wilting, 2018). These approaches are the least dependent on assumptions as only the share of the (future) global population determines the budget per person. The other approaches are used to see to what extent they are realistic and to estimate the probability that these can be achieved.

At first, an important note need to be made in relation to Haven-Stad. Haven-Stad is an urban neighbourhood where energy is predominantly used in houses, office buildings and for cars. The carbon footprint of the energy system in the neighbourhood is therefore relatively low as no energy is used for industry, agriculture and large transport which are not included in the footprint of Haven-Stad, but the inhabitants do make use of. Industry and transport are together responsible for 58% of the final energy consumption nowadays (IEA, 2019). Besides, the carbon budget is about the total emissions, including also non-energy related emissions like in the agricultural or industry sector. Currently, the GHG emissions in the Netherlands are distributed across sectors as shown in table 7. This gives an indication on how the energy related emissions compare to the total emissions, but as this study is about 100% renewable energy systems, it is not accurate for a situation with 100% renewable energy. A renewable energy systems would change the total emissions, and the extent to which each sector contribute, as each sector makes use of energy. If all energy is renewable, GHG emission in energy intensive industries will reduce drastically as well.

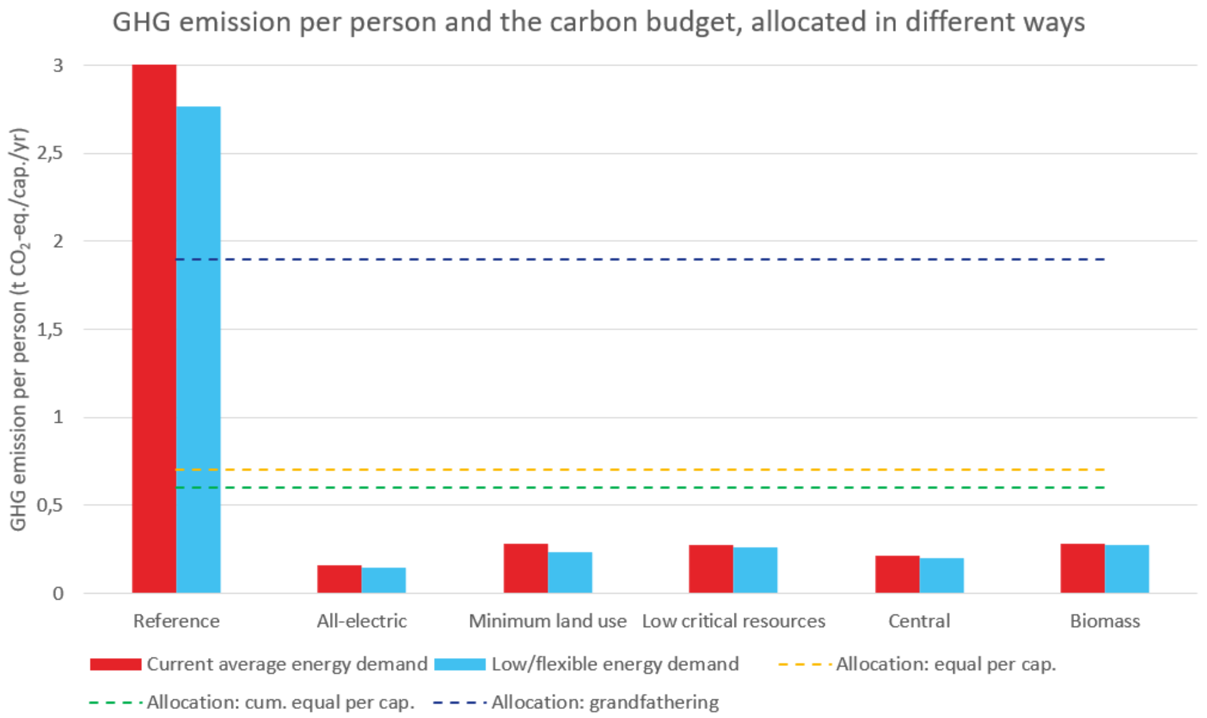


Figure 9 - The lifecycle GHG emissions of each design (based on two different energy demands). Horizontal lines represent the carbon budget to stay below 1.5 °C, allocated using different principles. Allocation based on 'ability to pay' and 'development rights' of respectively -1.7 and -6.6 t CO_2-eq./cap./yr are not shown in the figure

The energy consumption, and corresponding GHG emissions, for Haven-Stad consists of the energy, mobility and built environment sector that are together responsible for around 55% of the current GHG emissions and 40% of the energy consumption (see table 7). As the renewable designs contribute only for 21 to 39% of the carbon budget (equal per capita of 0.7 t CO_2-eq./cap./yr), no renewable design exceeds this budget and is per definition unsuitable in the light of GHG emissions. If the shares in GHG emissions of different sectors remains equal, the carbon budget (equal per capita) will not be exceeded as the renewable designs contribute for 21 to 39% to this carbon budget and the share of the electricity, mobility and built environment sector are currently together 55%. But as the development in each sector cannot be predicted, no firm statements can be made.

Where the total carbon budget of 400 Gt can be seen as a strict and fixed limit, the allocation for the Netherlands and the assumption that the budget is spread equally over the years up to 2100 is debatable. If the carbon budget was spread out equally over the years up to 2060, the allowed emissions per year are twice as much as with the assumption for 2100. As the Paris agreement and Dutch climate agreement have the goal of staying below 2.0 °C and striving for 1.5 °C (Klimaatakkoord, 2019), it could also be argued that exceeding the carbon budget for 1.5 °C is still within manageable global warming boundaries, as long as it stays well below the carbon budget for 2.0 °C. The carbon budget for 2.0 °C is more than twice as high as the carbon budget for 1.5 °C (respectively 840 and 400 Gt CO_2-eq.), so the horizontal lines that represent the 1.5 °C carbon budgets are not strict limits but more an indication that is not per definition problematic to be exceeded.

What could be said is that the goal of staying well below 2.0 °C and striving 1.5 °C temperature increase is realistic to be achieved on the basis of the contribution of the different renewable designs and the estimation for the contribution of other sectors. Especially the 'all-electric' design has low GHG emissions due to the fact all heat is produced with heat pumps that require less electricity than it produced heat, causing a lower primary energy use. Besides, a small share of biomass is incorporated.

A last notion about the emissions in other sectors is that the agriculture sector has a share of 14.4% in GHG emissions and only 5.4% in energy consumption (see table 7). This is due to the fact that this sector emit a higher share of GHG emissions that are not related to fossil fuels and energy. Therefore, the exclusion of fossil fuels will have a lower GHG reducing effect on the agricultural sector than on energy intensive sectors like the industry, energy, transport, household and services sector. The relative contribution of agriculture to the total GHG emissions is therefore likely to increase if all energy is produced from renewable sources.

Table 7 - Current share of each sector in the total GHG emissions (CBS, n.d.) and in the final energy consumption in the Netherlands (CLO, 2019).

Share in GHG emission	
Industry	30.8%
Electricity	22.9%
Mobility	19.2%
Agriculture	14.4%
Built environment	12.7%
Share in energy consumption	
Industry	41.6%
Transport	14.9%
Households	13.1%
Energy sector	12.0%
Services	9.3%
Agriculture	5.4%
Other	3.7%

Regarding the two different energy demands, a first logical notion to make is that the GHG emissions are lower with low/flexible energy demand than with current average energy demand. A second effect is that the impact of a flexible share of electricity demand is higher if a higher share of intermittent electricity sources are incorporated. This can be seen by the fact that the relative reduction in GHG emissions is the highest for the minimum land use design. In this design, no biomass is used, so all electricity is produced by wind and solar PV. For a share of the electricity demand that can be shifted, the demand can be better matched to the intermittent production so a higher share of the energy can be used on the moment when the production is high. In that way the intermittent sources can be used in a more efficient way and less energy has to be curtailed/stored. The remaining designs use biomass (to a different extent) that can be used when necessary, without the uncertainty of weather conditions. The reduction in GHG emissions of the reference designs and the designs with a higher share of biomass can be attributed to the lower heat demand, so a smaller amount of heat has to be produced.

4.2.1 Potential for negative GHG emissions

The GHG emissions in figure 9 are far above the carbon budgets based on ‘ability to pay’ and ‘development rights’, but that is because of the fact that this study does not include BECCS, so negative emissions are not possible. In this chapter the potential for negative emissions is calculated to get an indication whether the negative emissions of the carbon budget on the basis of ‘ability to pay’ and ‘development rights’ are feasible or not. As solid biomass contains 109.6 kg CO_2/GJ (395 g/kWh) (Zijlema, 2015), and the post-combustion carbon capture efficiency is around 90% (Kato and Yamagato, 2014), the CO_2 that potentially can be captured is 356 g/kWh of primary bioenergy. The table below shows the potential amount of carbon that can be captured from biomass energy production in each design.

Table 8 - Potential GHG emission capture due to BECCS in each scenario for both 'current energy demand' and 'low/flexible energy demand'. In t CO2-eq./cap./year.

	Current energy demand	Low/flexible energy demand
Reference	0.18	0.18
All-electric	0.31	0.28
Min. land use	0	0
Low critical resources	1.96	1.85
Central	1.15	1.09
Biomass	2.32	2.21

To get an indication of how negative the total emissions of the energy system for Haven-Stad could be, a simplified figure (figure 10) is made in which the potential captured CO_2 is deducted from the GHG emissions without BECCS that are shown in figure 9. In reality, the required energy to capture the CO_2 increases the total energy demand in the system what will increase the total emissions slightly. This figure is only to see if it is possible to reach the -1.7 and -6.6 t CO_2-eq. per person.

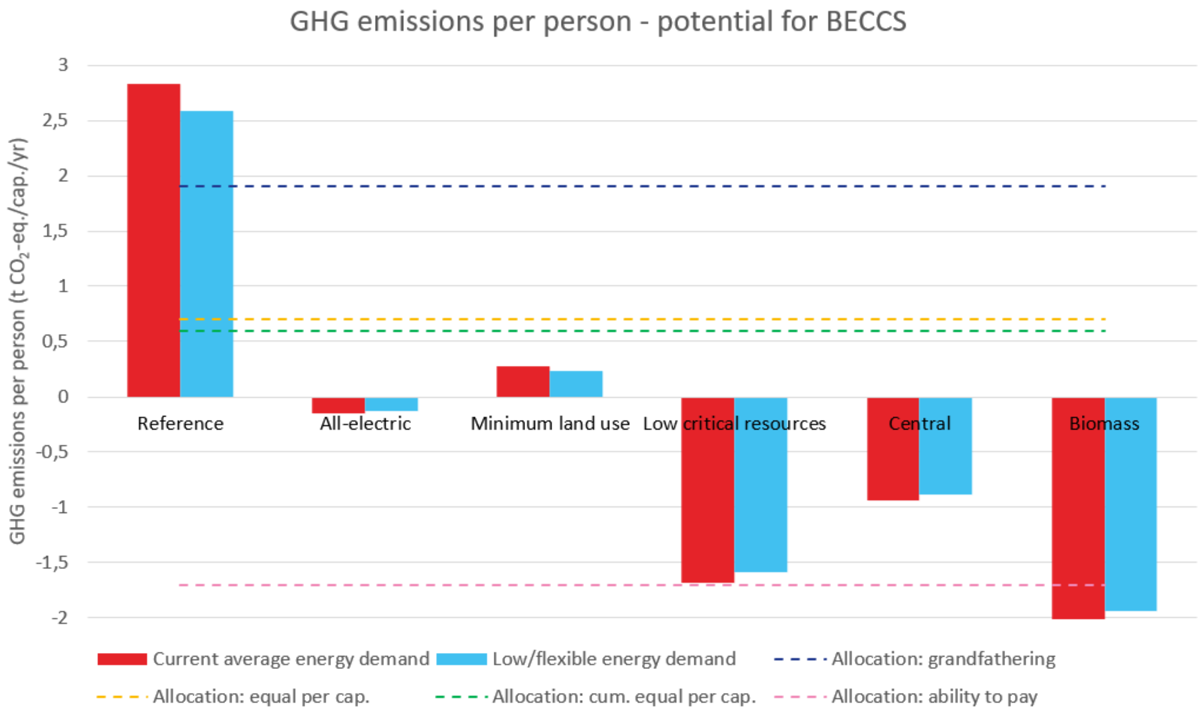


Figure 10 - The lifecycle GHG emissions of each design (based on two different energy demands) minus the potential BECCS. Horizontal lines represent the carbon budget to stay below 1.5 °C, allocated using different principles. Allocation based on 'development rights' of -6.6 t CO_2-eq./cap./yr is not shown in the figure.

From this simplified figure can be seen that the GHG emission in the minimum land use design do not change as this design does not use any biomass. The designs with the most biomass incorporated has the most negative GHG emissions but even the biomass design that is predominantly fuelled by biomass does not come close to the -6.6 t CO_2 per person, so this is an unrealistic carbon budget that cannot be achieved with renewable energy systems. The -1.7 t CO_2 per person ('ability to pay' carbon budget) can probably be achieved if nearly all energy in the system is produced by biomass.

4.2.2 Carbon intensity of electricity production

There are a lot of uncertainties in interpreting the carbon footprint of an energy system in comparison to the total carbon budget. It is hard to say to what extent it is problematic that a particular energy system design is responsible for e.g. 50% of the total carbon budget because the contribution of other sectors to total emissions is hard to estimate with a decarbonized energy system. Therefore the energy system of Haven-Stad is also compared to the carbon intensity that is mentioned in sustainable scenarios in IPCC and IEA reports that have a broader scope than only the energy system (explained in section 4.1.1). So the carbon intensity of electricity production is determined while considering the energy sector as part of the total system. This is an advantage as it can be compared to the carbon intensity of electricity production for the design for Haven-Stad, but it is a disadvantage as a lot of assumptions are made in these scenarios with regard to total electricity requirement, population growth, the distribution of emissions and energy across regions and sectors, etcetera. Therefore the carbon intensity is only used to see if it is in the same order of magnitude of the carbon intensity of Haven-Stad.

In the figure below, the carbon intensity of electricity production in the different designs is presented, together with the reference value from the IEA and IPCC scenarios. As can be seen, each design (except for the reference design) has a carbon intensity that is comparable to the carbon intensity in the sustainable scenarios of the IPCC and IEA for 2050. This indicate that the electricity production in Haven-Stad are comparable to global scenarios in which the temperature increase is limited to 1.5 °C – 2.0 °C. For carbon intensity, it is irrelevant that the energy system of Haven-Stad do not include any industrial/agricultural activity since the carbon emissions are expressed as a relative value.

The carbon intensities in the ‘low critical resources’ and ‘biomass’ are higher than in the other renewable design. This is due to the fact that in these designs a higher share of the electricity is produced by biomass in a CHP and/or PP with an assumed electric efficiency of 30% (Padinger et al., 2019). Electricity production from biomass has the highest carbon intensity of each renewable energy source (table 6). As biomass is predominantly used in CHPs in the designs, also heat is produced so the overall efficiency is higher that only the electric efficiency.

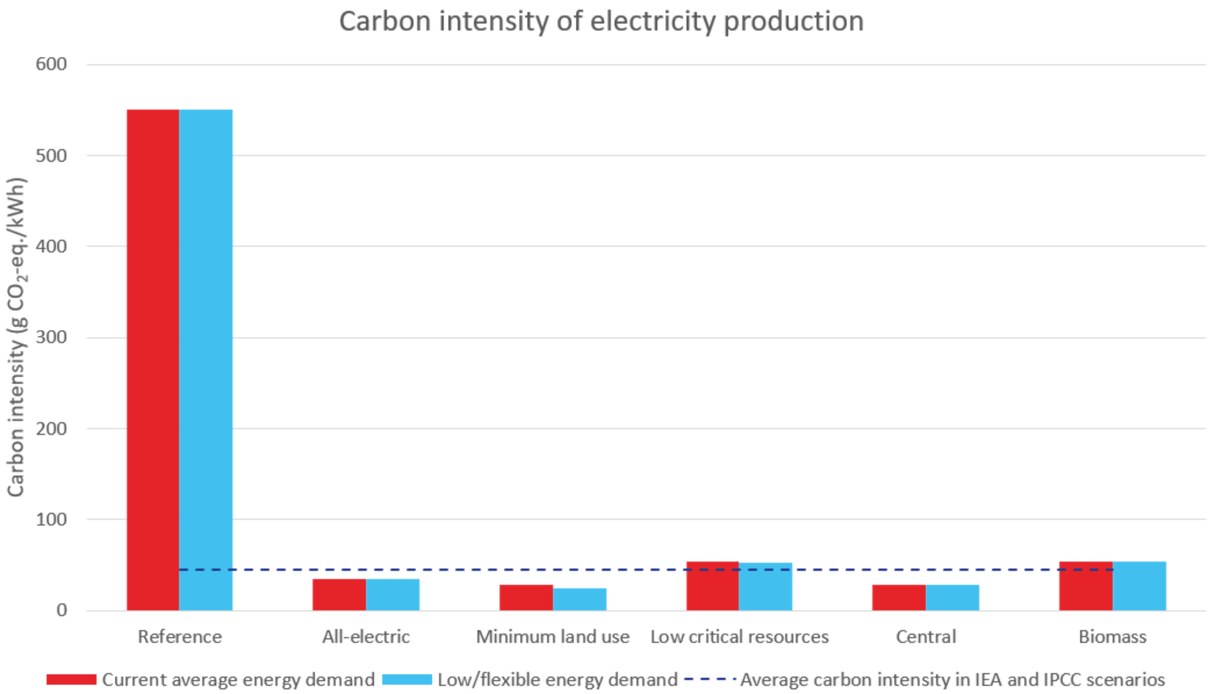


Figure 11 - The carbon intensity of the energy supply in each design and the indicative sustainable limit value.

In general could be said that 100% renewable energy systems (in each design) have comparable carbon intensities as in the sustainable scenarios, as long as the amount of solar PV is not too high, as well as biomass if it is used in an inefficient way; for example in a power plant with an efficiency of 30%. The higher the share of biomass in a design, the higher the potential captured CO_2 is, if CCS is applied to bioenergy. This can be derived from figure 9 where can be seen that the biomass design has potentially the lowest emissions because that design includes the highest amount of biomass. So when BECCS is applied in the energy system, a higher share of biomass is preferred with respect to the GHG emissions.

4.3 Sustainable reference values land use

For energy generation from fossil fuels, land use occur predominantly in upstream and downstream processes, depending on type of mining or extraction, supply infrastructure and waste disposal (Sathaye et al., 2011). For renewable energy sources, land use in the operational phase is the major contributor, except for bioenergy from dedicated feedstocks (Sathaye et al., 2011). The conversion of forests, grasslands, wetlands and other types of vegetation into agricultural land with the purpose of energy production, causes a reduction in biodiversity, impacts on water flows, and on the biochemical cycle of carbon, nitrogen, and phosphorus (Stockholm Resilience Centre, n.d.).

If energy supply technologies can be incorporated in land with other purposes, the land use change is lower because the land can still be used for its prior function (Evans et al., 2009). For example if PV panels are mounted to roofs or wind turbine are located in agricultural land. This dual purpose allocation is often not taken into account in the land requirement mapping. Looking at land use intensity of energy generation, it is striking that for the same generation source/technology the value vary a lot between different data sources. but the order of the different energy sources is generally the same. In general, non-renewable energy sources have the lowest land use per kWh, but in the same order of magnitude as non-biomass renewables, while bioenergy has by far the largest land requirement (Fritsche et al., 2017). This trend is seen in nearly all consulted articles (Fthenakis and Kim, 2009; Horner and Clarke, 2013; Evans et al., 2009; Bonamente et al., 2015; Gibon et al., 2017; Evans et al., 2010; Fritsche et al., 2017; Hertwich et al., 2015).

In the table below, the land use intensity is shown for the various energy sources. Different data sources give varying and sometimes contrasting data regarding the land use for energy production (Fthenakis and Kim, 2009). That can also be seen in the table below. The median value will be used for the calculation of the land use footprint of the sustainable scenarios for Haven-Stad. In appendix C is explained more extensively how the land use impact of the energy system designs is calculated.

Table 9 - The land use intensity of different energy sources.

	Land use intensity (m²/MWh)	Median
Coal	5.64 – 9.7 [2, 3, 4]	5.64
Natural gas, electricity	4.35 – 18.6 [2, 3, 4]	5.73
Natural gas, primary energy	3.44 [based on 2, 3, 4]	3.44
Wind	32.6 – 72.1 [2, 3, 6]	48.3
Solar PV	8.7 – 36.9 [1, 2, 3, 5, 8]	17.1
Biomass electricity	450 – 543 [1, 2]	496.5
Biomass heat	175 *	175
Biomass, primary energy	149 *	149
Geothermal heat	0.4 [9]	0.4
Solar thermal heat	2.9 [7]	2.9

Data sources: 1: Fritsche et al. (2017); 2: McDonald et al. (2009); 3: Stevens et al. (2017); 4: Swain et al. (2015); 5: Ong et al. (2013); 6: Rinne et al. (2018); 7: Van der Ploeg, 2012) 8: National energyAtlas, n.d.; 9 Bronicki, 2018. * The land use intensity of biomass (primary) and biomass (heat) is derived from data from Fritsche et al. (2017) and McDonald et al. (2009), and adjusted based on efficiencies of energy conversion technologies from Padinger et al. (2019) and Hebenstreit et al. (2011).

With 10% of the global energy supply, biomass is currently the renewable energy source with the highest share in global energy supply. The demand for bioenergy is expected to increase significantly because of EU policy targets with the aim to reduce GHG emissions and become less dependent on fossil fuels (Schutter and Giljum, 2014). As a result, the land use impact of renewable energy systems increases as well. As land is scarce, the competition for available land between crops grown for food and dedicated energy crops will increase if the bioenergy demand increases (Henry et al., 2018). Because bioenergy has by far the highest land requirement per kWh, biomass is the most common renewable source, and all future renewable scenarios incorporate a significant share of bioenergy, the land use footprint of energy systems will be determined predominantly by bioenergy.

The planetary boundary to keep the impact of land use within sustainable boundaries is defined by a maximum of 15% of the global ice-free land surface to be covered by cropland (Lucas and Wilting, 2018; Henry et al., 2018). The global ice-free land surface is approximately 132 million km² (IPCC, 2019; Ritchie, 2017; Henry et al., 2018). As the planetary boundary allows a maximum of 15% of this area for cropland, the maximum global cropland area is 19.8 million km². Cropland can be used for renewable energy production on the remaining land if a sufficient amount of food is provided. The required cropland area for human and animal food depends on future diets, population growth and productivity (Harvey, 2010; Cornelissen et al., 2012). Wirsenius et al. (2010) state that the required cropland area to provide for global food production is between 16.2 and 17.2 million km² in 2030, depending on future diets and productivity (Wirsenius et al., 2010). This data include also land requirement for non-food crops (mainly cotton and rubber) (Wirsenius et al., 2010). If the average value of the scenarios is taken, the cropland requirement for food is 16.8 million km². The remaining land area before the planetary boundary is reached is 3.0 million km² (19.8 minus 16.8). This corresponds to 385 m² per person with a global population of 7.8 billion. In studies that incorporate sustainability criteria like water use, biodiversity protection, soil protection, degradation of land, deforestation, carbon stocks and sustainable use of residues and waste, the used land area for renewable energy is between 2.35 and 4.35 million km² which is comparable to the 3.0 million km² proposed in this study (Field et al., 2008; Campbell et al., 2008; Cornelissen et al., 2012).

Many studies exclude the extraction from primary forests because of the adverse impact on biodiversity and carbon stock. Even the studies which estimate more than 600 EJ of bioenergy potential, exclude forest biomass as a source (Slade et al., 2014). Because of the impact on carbon stock, land use (change), water use, biodiversity and soil quality, direct forest extraction is excluded (Nakada et al., 2014). Besides, the planetary boundary about deforestation is already crossed substantially so no land use in current forestland for energy production can be incorporated (Steffen et al., 2015).

4.3.1 Potential energy production on available land

With the data in table 9, the expected population of Haven-Stad and the assumption that electricity production from biomass has an efficiency of 30% (Padinger et al., 2019), could be calculated that the available primary bioenergy for Haven-Stad is 330 GWh/yr. From different articles becomes clear that the primary energy yield from dedicated energy crops is approximately between 150 and 350 GJ/ha/yr, depending on the type of biomass (Harvey, 2010; Kulig et al., 2019, Boehmel et al., 2008, van der Ploeg et al., 2012; McKendry, 2002). With a primary energy yield of 250 GJ/ha/yr, the primary energy yield for Haven-Stad is 340 GWh/yr with the assumed 385 m² per person and around 120000 inhabitants. This is more or less equal to the calculation above, based on the land use intensity in table 9. Using the electric efficiency of 30%, the land use intensity of primary bioenergy is 149 m²/MWh. As biomass heat production (trough boilers) can reach thermal efficiencies of 85% (Hebenstreit et al., 2011), the land use intensity of heat from biomass per boiler is 175 m²/MWh. These data are shown in table 9 and used to calculate the land use impact of Haven-Stad. These calculations can be found in Appendix C and D.

Besides the 385 m² per person of available cropland for bio energy, also a certain amount of energy can be generated from biomass residues and waste including forestry residues, wood waste, oils, fats, agricultural residues, dry waste, wet waste and residues (Cornelissen et al., 2012). According to a study that takes into account a comprehensive set of sustainability criteria, the global potential for this category of waste and residues is 101 EJ of primary energy (Cornelissen et al., 2012). This correspond to 3.6 MWh per person per year of primary energy, which is more than what could be produced from 385 m² cropland.

4.3.2 Land use of non-biomass renewables

Biomass for energy production is not bounded to the location where the energy is expected to be consumed because biomass (in the form of pallets or chips) can be transported relatively easily, in contrast to electricity and heat. Therefore biomass is discussed at global scale as the necessary biomass can be imported from anywhere. Land use for other renewable energy sources needs to be analysed at smaller geographical scale because they need to be located more closely to the local of final energy consumption. This is due to the fact that land use of e.g. solar PV and wind is mainly caused in the operational phase and for bioenergy it is primarily due to the upstream process of crop cultivation (Sathaye et al., 2011). Therefore land use for wind and solar energy generation is analysed on national scale.

To give an argued estimation of the potential energy production within the Netherlands for wind and solar PV, while taking into account sustainability, the study of van der Ploeg et al. (2012) is consulted. In this study, the technical potential is determined without looking at spatial, emotional and financial restrictions but considering three limitations; the current function of an area will not be changed, regulations need to be taken into account (e.g. no wind turbines within 500 meter of houses), and where possible the demand and supply of energy will be matched locally (van der Ploeg et al., 2012). The potential energy production of several renewable technologies are calculated for the Dutch region 'Stedendriehoek' which is spatially representative for Netherlands regarding both rural and urban areas (van der Ploeg et al., 2012). Therefore, it is assumed that the potential energy production is representative for the Netherlands. The technical potential of onshore wind and solar PV are respectively 46.81 and 21.50 TJ/km²/yr (van der Ploeg et al., 2012). Knowing that the surface area of the Netherlands is 41543 km² of which 33671 km² is land (CBS, 2018a), the national potential of onshore wind and solar PV is respectively 1576 and 724 PJ/yr. With the assumption of a Dutch population of 17.4 million (CBS, 2020b), the potential energy production per person could be calculated that is shown in the table below.

Table 10 - Potential energy production in the Netherlands (based on Van der Ploeg et al., 2012)

	Onshore wind	Solar PV
Potential energy production in NL (TJ/km²/yr)	46.81	21.50
Potential energy production in NL (PJ/yr)	1576	724
Potential energy production per person in NL (GJ/cap./yr)	90.6	41.6

To come to the data above, a couple of assumption made by van der Ploeg et al. (2012) are used. Namely an energy production of 120 kWh/m²/yr for solar PV and wind turbines of 3 MW that produce 21.6 TJ per year. For the full set of assumptions and underlying ideas, the study of van der Ploeg et al. (2012) can be consulted. These technical potentials are considered as sustainable since it only incorporates the potential that can be achieved without changing the existing land function. In the calculations for potential energy production per unit surface area, only considerations are made regarding technical, legal and sustainability aspects. In reality, choices for land use allocation (for renewable energy production) are also determined by political, social and economic aspects (RVO, 2016).

The reference values that are used to compare the land use impact of the designs for Haven-Stad to are the maximum cropland use for bioenergy (385 m²/person) and the potential energy production per person for wind and solar PV without land function change. Also the total land requirement in relation to the surface area of Haven-Stad is considered, as well as distribution between land requirement in the Netherland and at global scale.

4.4 Land use impact of the energy system designs for Haven-Stad

In the figure below, the land use impact of the energy system designs is shown. The reference design has by far the lowest land requirement of all designs. This confirms what is mentioned before; land requirement is one of the environmental impacts that increases when fossil fuels are replaced by renewable sources. It is a logical consequence of the fact that energy generation on the basis of fossil fuels has generally a smaller land use footprint than renewable alternatives.

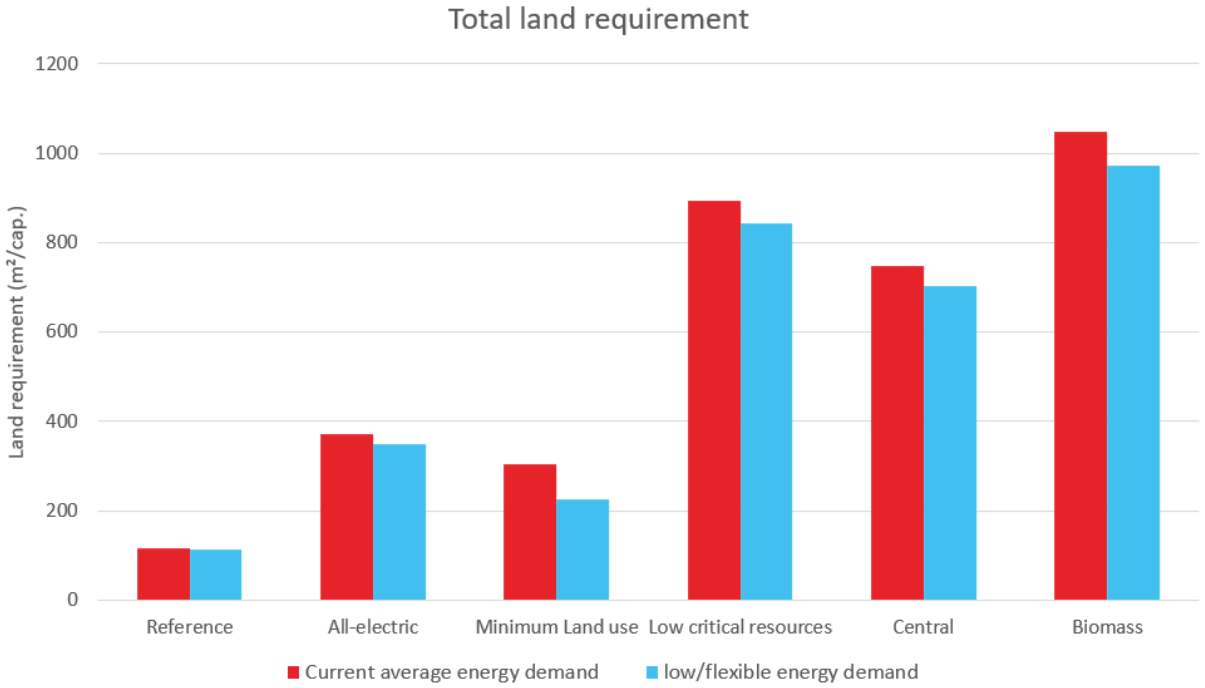


Figure 12 - The total land requirement per person for each of the designs

Another striking note that can be made from figure 12, is that the minimum land use design has still a considerable amount of required land in relation to the other renewable designs, despite of the exclusion of biomass in this design. Especially the all-electric design comes close because this design uses a low amount of biomass relative to the other renewable designs. Biomass is by far the largest contributor to land use in relation to the other energy sources (see table 9). The use of biomass has an additional downside regarding land use that is not reflected in the figure. This is because the most common alternatives, wind and solar PV, can be incorporated in land with other purposes what is not taken into account in these numbers (Evans et al., 2009). If solar PV is mounted to roofs, the required land is still functional as roof which was already there, so the additional land use is more or less zero. A similar dual purpose allocation often takes place with onshore wind and to a lesser extent offshore wind. For biomass dedicated for energy, this is different as the land necessary to grow the crops can be used in combination with e.g. onshore wind, but then another purpose is incorporated in the bio-crops land area instead the other way around. Therefore the land use reducing effect of dual purpose allocation is bigger for wind and solar PV than for bioenergy. The figure below shows the extent to which the different energy sources contribute to the total land requirement of each design.

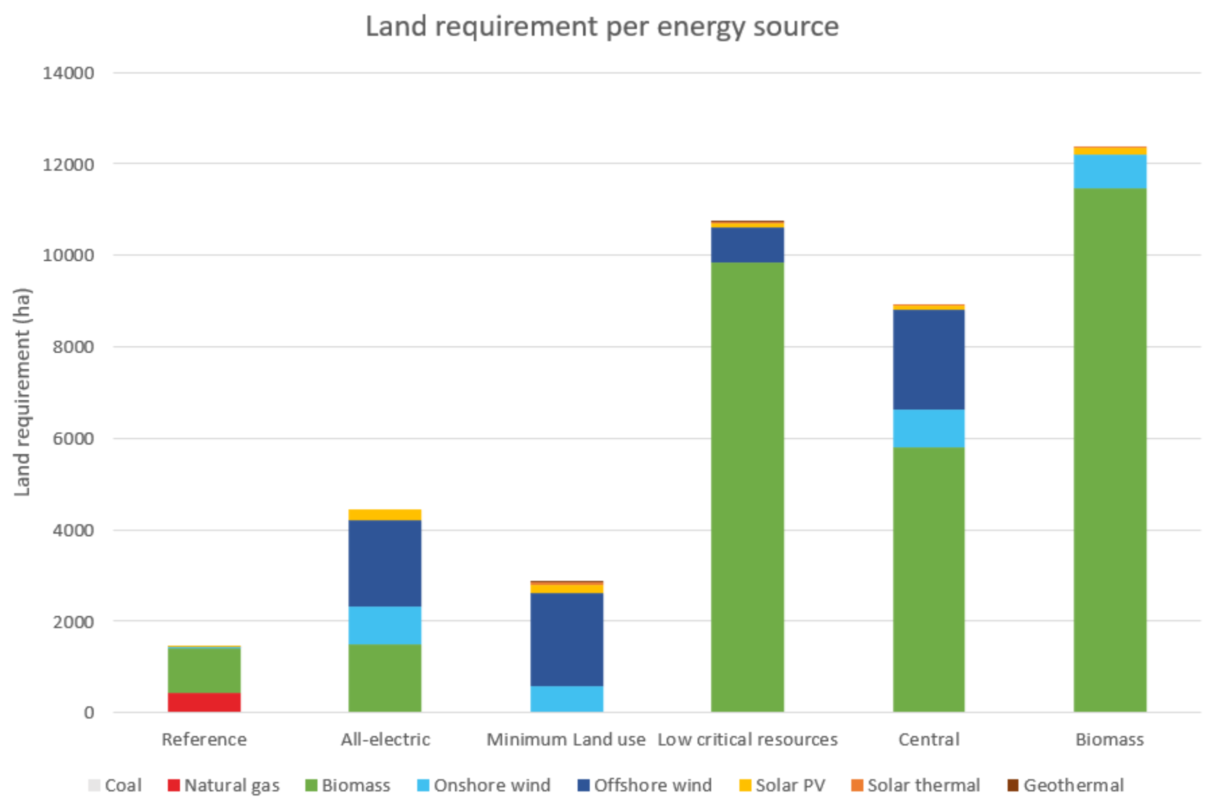


Figure 13 - Total land requirement for each energy system design and the contribution of each energy source. Figure for low/flexible energy demand. The figure with current average demand looks similar.

What is striking in the figure, is that the land use footprint of the energy systems are largely determined by biomass. Even in the reference design with the smallest share of bioenergy in the total energy supply, biomass is responsible for around 70% of the land use footprint while around 80% of the energy is produced natural gas. The second thing that is striking, is that the all-electric and minimum land use design have the highest share of solar and wind energy, and the lowest share of biomass. Based on the principle of dual purpose land use, these two designs have the potential to have a significantly reduced land use impact if the installed wind and solar PV is located on land that is already used for another purpose without changing the original function. There is no limitless potential of locations where energy could be generated without changing the original land function. Therefore the amount of installed wind and solar PV is compared to the technical potential in Netherlands to see whether it is possible to implement such an amount of wind turbines and solar PV without changing the original land function (as explained in section 4.3.2). The table below shows the energy production per person from onshore wind and solar PV in each design, as a percentage of the technical potential per person without land function change.

Table 11 - Installed capacity per person in Haven-Stad as a percentage of technical potential per person without changing the original land function (based on van der Ploeg et al., 2012).

	Onshore wind	Solar PV
Reference	0.11%	0.13%
All-electric	6%	10%
Minimum land use	5%	9%
Low critical resources	0%	3%
Central	6%	4%
Biomass	5%	5%

From this result could be concluded that all designs could be realised without being constrained by a shortage of available land for wind turbines and solar PV without land function change. Even if all offshore wind would be located on land, there is a sufficient area available in the Netherlands to implement it. As there is still so much land available where potentially solar PV can be placed without land function change, there is enough place to allocate the solar thermal collectors that are incorporated in the designs. For the feasibility of the designs, also social, political and economic trade-offs are important but this research focusses only on the technical possibilities and sustainability aspect.

To place the total amount of required hectares for the energy systems in perspective, the land area of the Haven-Stad neighbourhood is only 650 m² (excl. water) (Gemeente Amsterdam, 2017). The required area for the energy production in the renewable design is 4.5 to 19 times higher than the surface area (excluding water) where the energy is consumed; Haven-Stad. In an urban area with a high population density like Haven-Stad, it is logical that the land requirement for energy in relation to the surface of the neighbourhood itself is higher than for a rural area. In the table below, the total area required for energy production is shown for each design, as well as the area requirement that occurs necessarily in the Netherlands. The latter is calculated by deducting land requirement for biomass from the total area requirement. This is because biomass can be imported from other countries but technologies for wind, solar PV, solar thermal, geothermal etcetera need to be located within the Netherlands. Below the table, the same data is shown in a figure on scale in which can be seen that biomass determine generally the total area requirement. Another thing that stands out is that the order of the designs changes if only the area requirement within the Netherlands is accounted for instead of the total area requirement. The minimum land use design has almost the highest land use if biomass is not taken into account. If the total land use impact increases due to the use of biomass, the impact within the Netherlands decreases because less other energy source are needed. This is only true if all biomass in imported. In densely populated regions/countries, (imported) biomass could be a good solution as it does not require land within the region and at the same time it reduces the need for other energy sources that require land within the region like wind or solar PV.

Table 12 - Total area requirement and area requirement in the Netherlands for each design (in ha).

	Total area required	Area required in NL
Surface area Haven-Stad	650	650
Reference	1436	460
All-electric	4434	2944
Minimum land use	2872	2872
Low critical resources	10727	893
Central	8934	3123
Biomass	12375	902

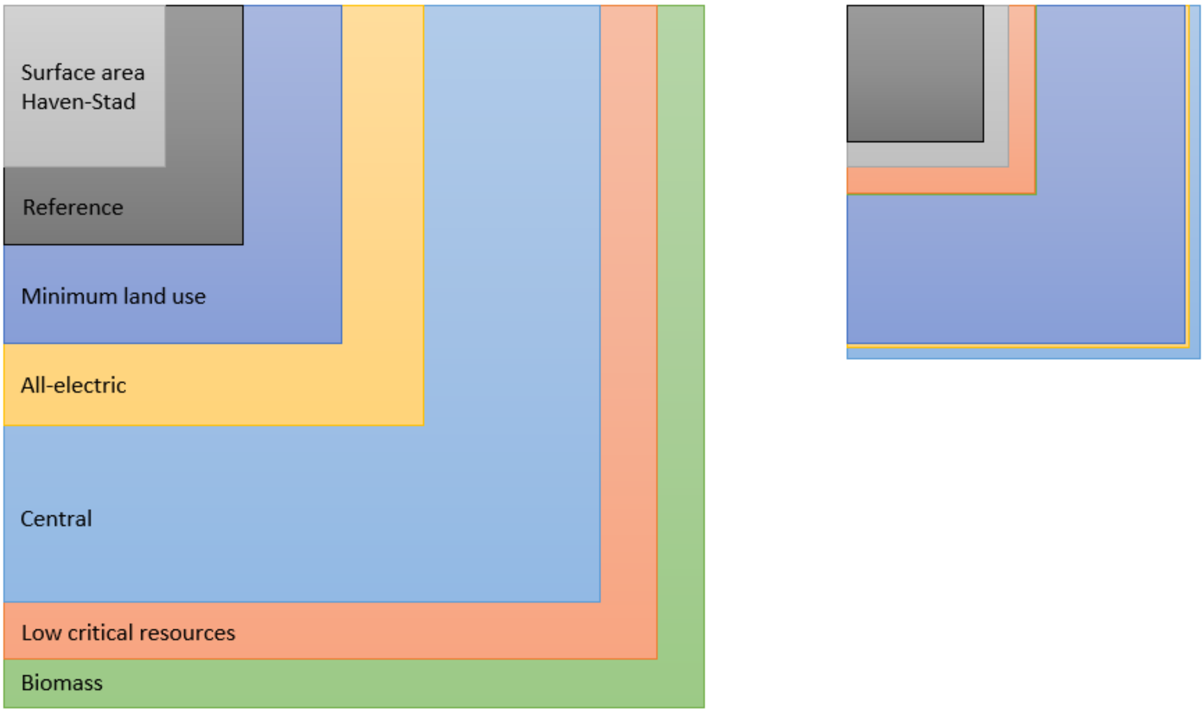


Figure 14 - schematic overview on scale of the land requirement for each design and the surface area of the neighbourhood where the energy is going to be used. Grey = Surface area of Haven-Stad, black = reference, dark blue = minimum land use, yellow = all-electric, light blue = central, orange = low critical resources, green = biomass. Left figure is total area requirement in the designs, right figure is the land requirement without biomass, what occurs in the Netherland. Both for low/flexible demand.

4.4.1 Biomass

The indicative limit value for a sustainable amount of land use that can be used for energy crops is based on the planetary boundary framework (for a detailed explanation and calculation see section 4.3). In the figure below, the area requirement per capita for each design is presented for both the 'current average energy demand' and the 'low/flexible energy demand'. The horizontal line represent the average maximum amount of cropland that can be used for energy per person; 385 m^2. This is the maximum amount of cropland that can be used to provide the total (average) energy demand, including heating, electricity, industry, agriculture, passenger and freight transport etcetera. The impact of the different designs are about the energy system in Haven-Stad that only consists of heat and electricity for building, and to provide for EVs. So bioenergy that is used in e.g. industry and freight transport for the use of the people in Haven-Stad is not taken into account in the area requirement in the designs.

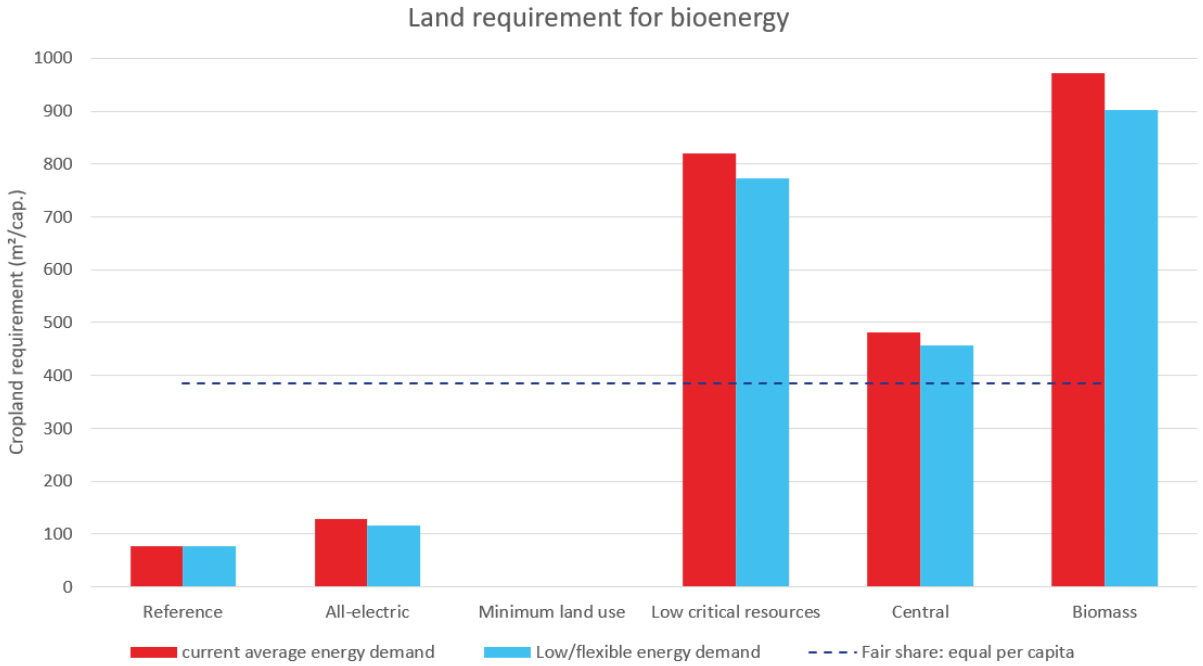


Figure 15 - Cropland requirement for each design for low/flexible energy demand and current average energy demand.

The reference, all-electric and minimum land use design do not exceed the indicative limit value of 385 m² by far. As they use only around 25% or 0% of the 385 m² of land, renewable energy systems do not by definition exceed the reference value for cropland use. The energy system of Haven-Stad do not represent the whole direct and indirect energy demand of the inhabitants so it could not said if the reference value for cropland use will be exceeded if all cropland use for bioenergy is incorporated. The remaining three designs exceed the limit value, for both the energy demands. This could cause problems as in these designs more land is used for energy production than the fair share per person would be with the principle of ‘equal per capita’ allocation of the global budget. If the fact is taken into account that the land use footprints only represent the electricity and heat supply in building, together with passenger transport by car, the land use impact would be even larger if the whole energy demand would be considered. Exceeding the equal per capita cropland budget for energy production within a certain region is not problematic, if the overall average cropland use is on or below that level. So if a certain country uses more biomass that can be yielded from 385 m² cropland, another region should compensate for that. As can be seen in the figure, that could be possible as even systems without biomass are possible. For densely populated regions with high competition for available land, it could be a solution to import biomass for energy as this reduce the energy demand from other sources that require land within the country/region like wind.

As the sustainable reference value represent only the available land to grow biomass dedicated for energy production, it does not include potential energy production from biomass residues and waste. According to a study that takes into account a comprehensive set of sustainability criteria, the global potential for this category of waste and residues corresponds to 3.6 MWh per person per year of primary energy (Cornelissen et al., 2012). The potential energy production at 385 m² cropland is 2.6 MWh per person per year what shows the total potential bioenergy that can be produced with waste and residues included is 2.4 times higher than what could be yielded from 385 m² cropland. This indicate that it could be possible to produce the amount of bioenergy that is incorporated in each design, but not only with primary dedicated energy-crops. Whether it is realistic and feasible on the short term is a discussion that is not part of this study since it aims to discover the possibilities to design a 100% renewable energy system within broad sustainable boundaries.

Another important aspect is the energy yield from biomass that is dependent on the type of biomass, location and circumstances under which the biomass grows. The land requirement of the designs is based on land use intensities that correspond to approximately 250 GJ/ha/year (see section 4.3.1). There are studies that show that the energy yield increases and that it could be already above 350 GJ/ha/year (Kulig et al., 2019). With a higher energy yield per m^2, the required area for the same amount of energy decreases.

So with an energy yield of around 250 GJ/ha/year and biomass from exclusively energy crops (no waste/residue), the land use budget as a fair share per capita will be exceeded in the central, biomass and low critical resources design. if a part of the biomass is substituted by residues/waste and the cultivation of biomass will occur more efficiently, the required amounts of biomass could achieved without exceeding the 385 m^2 cropland per person. The minimum land use and all-electric design show that it is possible anyway.

4.5 Sustainable reference for the use of critical resources

Renewable energy technologies are promoted in order to decrease the GHG emissions and avoid the depletion of fossil fuels (Fizaine and Court, 2015; Lieberei and Gheewala, 2017). However, renewable energy production technologies require higher amounts of (metal and mineral) resources being rated as potentially scarce (Lieberei and Gheewala, 2017). Since many (rare) metals and minerals are also necessary for other applications like electronics, industry and transport, the risk of resource depletion and the challenge of fair distribution of the available reserves/resources increases (Van Exter et al., 2018; Brooks, 2015). By including intermittent energy sources like wind and solar PV into the energy supply system, the need for energy storage technologies increases as well what goes along with additional use of potentially critical elements in the energy system (Corneau, 2018).

Criticality is generally seen as the nexus between security of supply and economic significance. Supply risk is an indicator for criticality that refers to the likelihood that supply could be restricted (Crock, 2016). Supply risk could be caused by limited reserves or resources, but supply shortages could arise as well due to a rapid demand increase (Watari et al., 2018). In literature, the critical resources related to renewable energy supply that are frequently mentioned are tellurium, indium, silver, dysprosium, neodymium and lithium (De Castro et al., 2013; Van Exter et al., 2018; Tokimatsu et al., 2018; Corneau, 2018; Giurco et al., 2019; Månberger and Stenqvist, 2018; Watari et al., 2018, Moss et al., 2011; Chu, 2011; Crock, 2016; Grandell et al., 2016). For these metals, the current production, global reserves and sometimes even the available resources are expected to be exceeded as a result of the shift towards a renewable energy supply system (Watari et al., 2018; Tokimatsu et al., 2017; Grandell et al., 2016). The metals that are used in the largest amount; aluminium, steel and copper, are not considered as critical resources (De Castro et al., 2013; Watari et al., 2018).

The renewable energy related technologies that require significant amounts of critical elements are solar PV, wind turbines, battery electricity storage, FCEVs and BEVs. Silver, tellurium and indium are used in different types of solar PV that are all commercially used. Silver in c-Si, tellurium in CdTe, and indium in CIGS modules (Giurco et al., 2019). Neodymium and dysprosium are used in the form of permanent magnets in wind turbines and EVs while lithium is used for battery electricity storage and in BEVs (Giurco et al., 2019).

In the chapter below, The global annual production, reserves, resources and material use intensities are shown, just as the other (non-energy) applications of the critical elements. The global resources of correspond to the total amount of a particular element that exists. By global reserves, the total amount of the resources are meant, that can be mined in an economically viable way under the current conditions (Giurco et al., 2019). Reserves change as cost of extraction, price of the metal and the technologies change over time (Watari et al., 2018). Over time, the known resources can increase if new resources are discovered, and resources can be upgraded to reserves if it becomes economically viable to mine them (Giurco et al., 2019).

4.5.1 Resources, reserves and annual production

The global resources, reserves and annual production are the sustainable reference points to which the use of critical elements in the renewable designs are compared to. The global resources and (to a lesser extent) reserves are a strict reference point that indicate the point at which the supply of the critical elements will be restricted or depleted what would constrain the further expansion of the related energy technology. As supply shortages could arise from rapid demand increase as well, the annual global production is a also a good indicator for possible restriction of material supply (Watari et al., 2018)

Table 13 - The global resources, reserves and annual production of each critical resource that is considered.

	Silver	Tellurium	Indium	Neodymium	Dysprosium	Lithium
Global resources (M kg)	1740 [4]	48 [3]	356 [7]	23000 [3]	1980 [3]	80000 [13]
Global reserves (M kg)	530 [1, 2, 3]	31 [6]	65 [8]	12800 [3]	1260 [12]	17000 [13]
Global Production (M kg/yr)	27 [5]	0.47 [6]	1.37 [9, 10]	27 [11]	1.8 [3]	77 [13]

Data sources: 1: Giurco et al. (2019); 2: Månberger and Stenqvist (2017); 3: Watari et al. (2018); 4: USGS (n.d.); 5: USGS (2020d); 6: USGS (2020b); 7: Werner et al. (2017); 8: European Commission (2015); 9: USGS (2020c); 10: Lokanc et al. (2015); 11: Crock (2016); 12: Hoenderdaal et al. (2013); 13: USGS (2020a).

The data above is relevant as it represents reference points that give an indication for the criticality of the resources. If the requirement of these particular metals are known, the resources, reserves and annual production give an opportunity to compare the metal requirement of Haven-Stad to, to see to what extent the neighbourhood's energy system contribute the demand and depletion of the metals. To map the resource requirement of Haven-Stad, the material use intensities of the resources in the energy related applications are necessary. These are shown in the table below.

Table 14 - Material use intensity of the critical resources in energy technologies (in kg/MW except otherwise indicated).

	Silver (c-Si PV)	Tellurium (CdTe PV)	Indium (CIGS PV)	Neodymium	Dysprosium	Lithium
Solar PV	23.75 [1, 2, 3, 4]	63 [5]	23 [5]	0	0	0
Wind turbine	0	0	0	180 [6, 7]	24 [6,7]	0
Li-ion battery	0	0	0	0	0	0.2 kg/kWh [9, 10]
(B/FC)EV	0	0	0	0.695 kg/EV [8]	0.083 kg/EV [8]	8.1 kg/BEV [8, 11, 12]

Data sources: 1: Giurco et al. (2019); 2: Moss et al. (2011); 3: Tokimatsu et al. (2018); 4: tokimatsu et al. (2017); 5: Redlinger et al. (2015); 6: Hoenderdaal et al. (2013); 7: Leader et al. (2019); 8: Watari et al. (2018); 9: Månberger and Stenqvist (2017); 10: Simon et al. (2015); 11: Gaines and Nelson (2009); 12: Duleep et al. (2011).

As solar PV, wind turbines, batteries and EVs are not the only products in which these critical elements are used, the other applications of the critical resources are shown in the table below as a share of the total demand. This is relevant in the interpretation of the requirement of the critical resources in Haven-Stad. If the energy system in Haven-Stad requires an amount of critical resources that uses nearly all reserves (relative per person), it would be a problem if that particular critical element is necessary in other application, and it would not be a problem if there is no other application of the particular critical element. This is used in the interpretation of the requirement of the critical resources in Haven-Stad. Neodymium and dysprosium are rare earth elements that are primarily used for the production of permanent magnets (Crock, 2016; Hoenderdaal et al., 2013). So called neodymium-iron-boron (NdFeB) magnets are the strongest magnets known and are used if little space and weight can be afforded.

Table 15 - The share of purposes to which the demand of the particular resource can be attributed.

Silver [1]	**Tellurium** [2]	**Indium** [3, 4]
c-Si solar PV modules (7.8%) Jewellery (20.6%) Coins/bars (17.5%) Electrical & electronics (24%)	CdTe solar PV modules (40%) Thermoelectric production (30%) Metallurgy (15%)	CIGS solar PV modules (8%) LCD displays (56%)
Neodymium [5, 6]	**Dysprosium** [7]	**Lithium** [8]
Permanent magnets (76%) (in NdFeB magnets, of which 41% used in industrial motors, 11% in electric devices, 5% wind turbines, 2% electric cars) Metallurgic alloys (8%) Batteries (5%)	Permanent magnets (NdFeB) (95%) Ceramic capacitors (5%)	Batteries (65%) Ceramics & glass (18%) Lubricant greases (5%) Polymer production (3%)

Data sources: 1: Alexander et al. (2019); 2: USGS (2020b); 3: Lokanc et al. (2015); 4: Redlinger et al. (2015); 5: Crock (2016); 6: Reimer et al. (2018); 7: Hoenderdaal et al. (2013); 8: USGS (2020a).

4.5.2 Comparison solar PV technologies

The three most commonly used solar PV module types are c-Si, CIGS and CdTe that require respectively silver, indium, and tellurium which are all three potentially critical elements (Giurco et al., 2019). These three technologies are compared to the annual production, reserves and resources of the critical element that the particular technology contains. This is done to see if there is one technology for PV that uses the least critical resources relative to their annual production, reserves and resources. In that case, the remaining technologies could be excluded from the remainder of this research. In this decision, the share of other purposes of the critical resources is taken into account as well (table 15).

The figure below shows that c-Si modules perform better that CIGS and CdTe in the light of critical resource requirement, relative to the corresponding global reserves and resources. For tellurium, the global resources per capita are already exceeded for the inhabitants of Haven-Stad when only around 0.1 kW/person of CdTe PV is installed for Haven-Stad. For indium, the global reserves per capita are exceeded when the installed capacity of CIGS modules reaches around 0.35 kW/person. As the reserves per capita are likely to be exceeded without taking into account other applications of the metals, c-Si modules can be considered as a better option for large scale application in the context of critical resource depletion. Even though the non-energy related applications of silver are relatively larger than for tellurium and indium, the required silver in relation to the global reserves and resources is so low that it still is the best option.

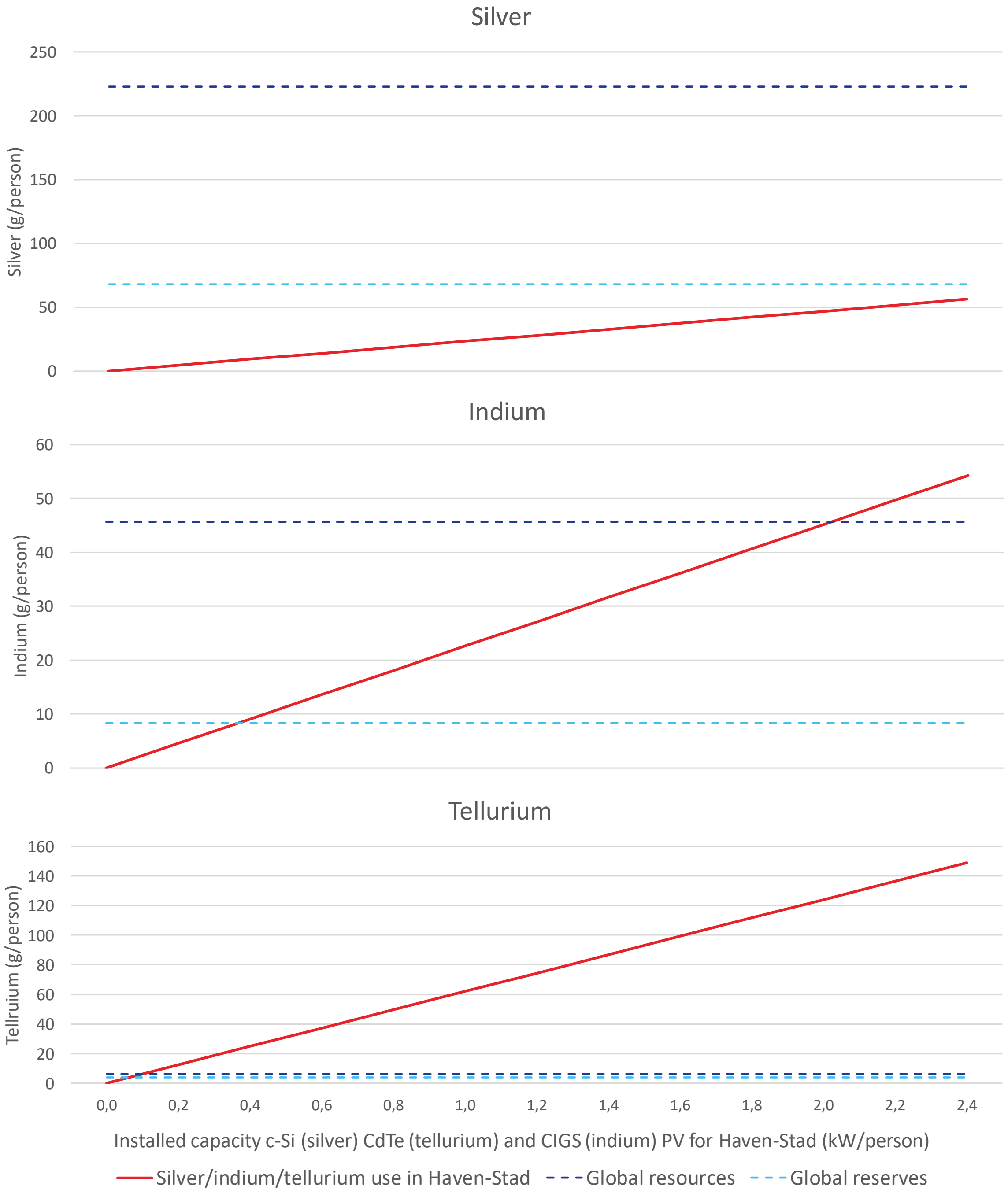


Figure 16 - The silver/indium/tellurium requirement per person in Haven-Stad for an increasing installed capacity of c-Si/CIGS/CdTe PV. The global reserves and resources as horizontal lines.

Besides the reserves and the resources, also the requirement in relation to the annual production is lower for silver than for indium and tellurium. The figure below shows the requirement for Haven-Stad as a percentage of the current annual production for an increasing installed capacity of the PV module types. The required silver is almost zero percent of the global annual production, even if 2.4 kW/person is installed. This shows that the size of silver production will not be a restricting factor for c-Si PV. As currently 7.8% of the global silver demand is used for PV, 88.7 GW/year of c-Si PV can be produced globally if 7.8% of the annual global production is used for c-Si panels. With the current annual global production of tellurium and indium, and the current share of PV in the demand (table 15), the production of CdTe and CIGS PV is respectively 3.0 and 4.8 GW/year. So with the current annual production and share within the total demand, there could be installed around 20 times as much c-Si PV than CdTe or CIGS PV modules.

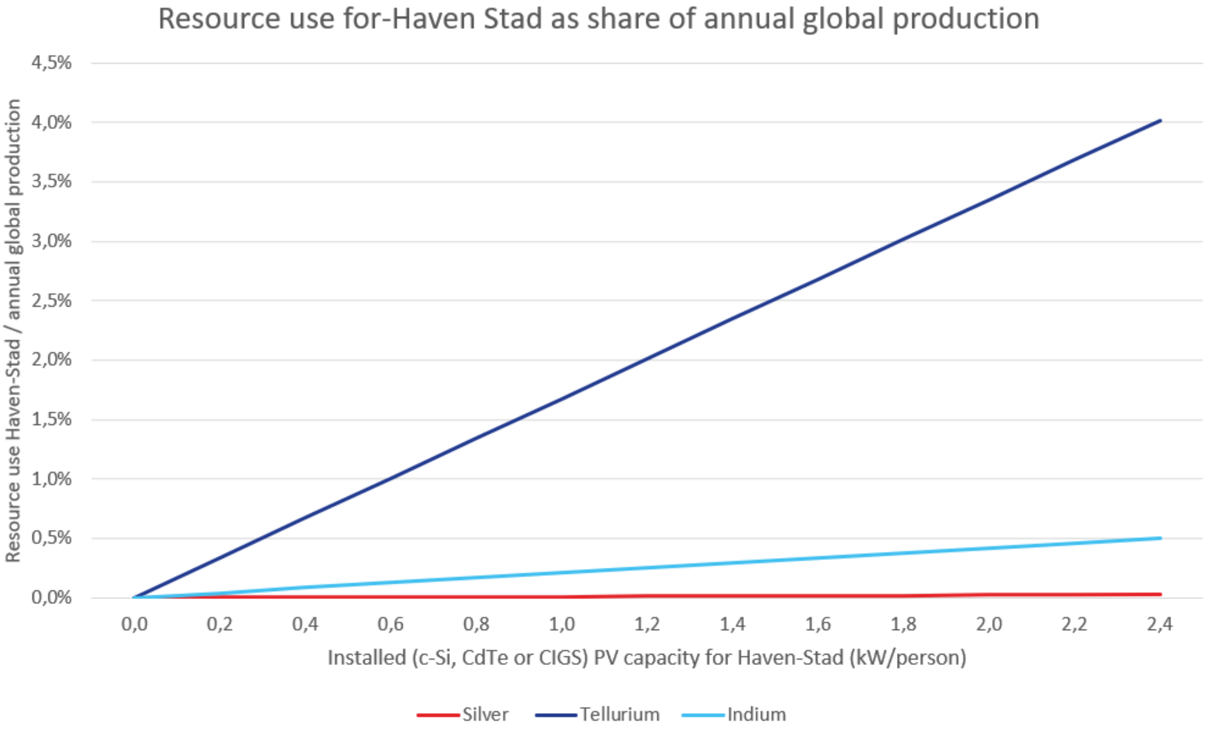


Figure 17 - The use of silver/tellurium/indium in Haven-Stad as a percentage of the annual global production of these critical resources for an increasing installed capacity of PV. The lines represent the material use if all PV capacity is of the type that contains their corresponding critical metal.

Finally, c-Si modules have a higher efficiency and they have currently by far the largest market share with 96% (multi-Si 76% and mono-Si 18%) compared to 6% of thin-film PV like CdTe and CIGS modules (Xu et al., 2018). Therefore, CIGS and CdTe modules are not considered anymore in the remainder of this study (just as tellurium and indium) because c-Si is considered as the best PV module type for large scale application. This does not mean that thin film PV cannot be preferable in other situations under different circumstances. Thin film PV is less expensive and enables lightweight and flexible modules as well, what could be the best solution under certain circumstances (Jean et al., 2015).

In the next sections, there is elaborated on the use of the critical elements for the energy system design for Haven-Stad in relation to the global resources, reserves and annual production.

4.6 The use of critical resources for the energy system designs for Haven-Stad

The use of critical resources in the energy system designs for Haven-Stad is compared to the global reserves, global resources and the current global annual production. These are analysed one by one in the chapters below.

4.6.1 Reserves

The use of critical resources per person for the energy systems in Haven-Stad in relation to the global reserves per person is shown in figure 18. As explained before, only c-Si PV is considered so it is assumed that all installed PV are c-Si modules that contain silver.

The imaginary horizontal line at 1 represents the situation in which the requirement of the critical resources in the energy system of Haven-Stad equals the global reserves per person. So if a particular material scores 1, it uses its fair share if the global reserves are allocated on the basis of 'equal per capita'. From the figure, a few things become clear. At first, the critical resource requirement in the reference design is so small that it barely can be seen in the figure. This confirms that the use of critical resources is a sustainability indicator that increases due to the shift from fossil fuels to renewable energy sources. Second, lithium is a critical metal from which is more required in three designs than the equal capita allocation of the global reserves. Only the amount of electric cars (29000 for around 120000 people) causes an average lithium use per person that almost equals the global reserves per person. The central design is the only design with no BEVs and no battery energy storage resulting in no lithium requirement. FCEVs require the critical metal platinum, so FCEVs are not naturally a better option than BEVs in the light of the use of critical resources. In contrast to lithium, the automotive industry is currently the major user of platinum, and the uptake of FCEVs increase the platinum demand but not to unfeasible amounts (Pollet et al., 2012). On the other hand, the platinum industry has currently the potential meet the requirement for 50% market penetration (Pollet et al., 2012). But as there are already plausible alternatives for platinum, and the platinum use intensity is decreasing over the past decades, it could be a good alternative to have a significant market share in addition to BEVs (Pollet et al., 2012).

For all renewable designs, except the central design, the required amount of lithium in relation to the reserves is so high that the reserves per person are exceeded. For the other critical resources, the energy system in Haven-Stad does not exceed the reserves per person. But the use of critical resources in the designs are only the resources that are used for the energy system, so if a design scores 1 in the figure below, there are no resources left to use them for other applications before the global reserves per person are reached. As there should be resources available for other applications, there should be looked at the use for other (non-energy related) purposes that are shown in table 15. If the share of the energy related application is low, like for silver, a higher share of the reserves/resources needs to be used for other purposes. That is why the small bar in the figure below for silver does not mean that it will not have consequences because the remaining demand is high. Since the silver use per person in Haven-Stad is higher than 7.8% in all renewable designs, the share in silver demand for PV should increase in relation to the other purposes, or a substitute/alternative should be found for PV. For neodymium and dysprosium the same can be observes. in each design, a higher share of the reserves per person is used for wind turbines and EVs than their share in the current demand. So to realise these designs at global scale, the share of EVs and wind turbines in the total use of permanent magnets need to increase in relation to the other purposes.

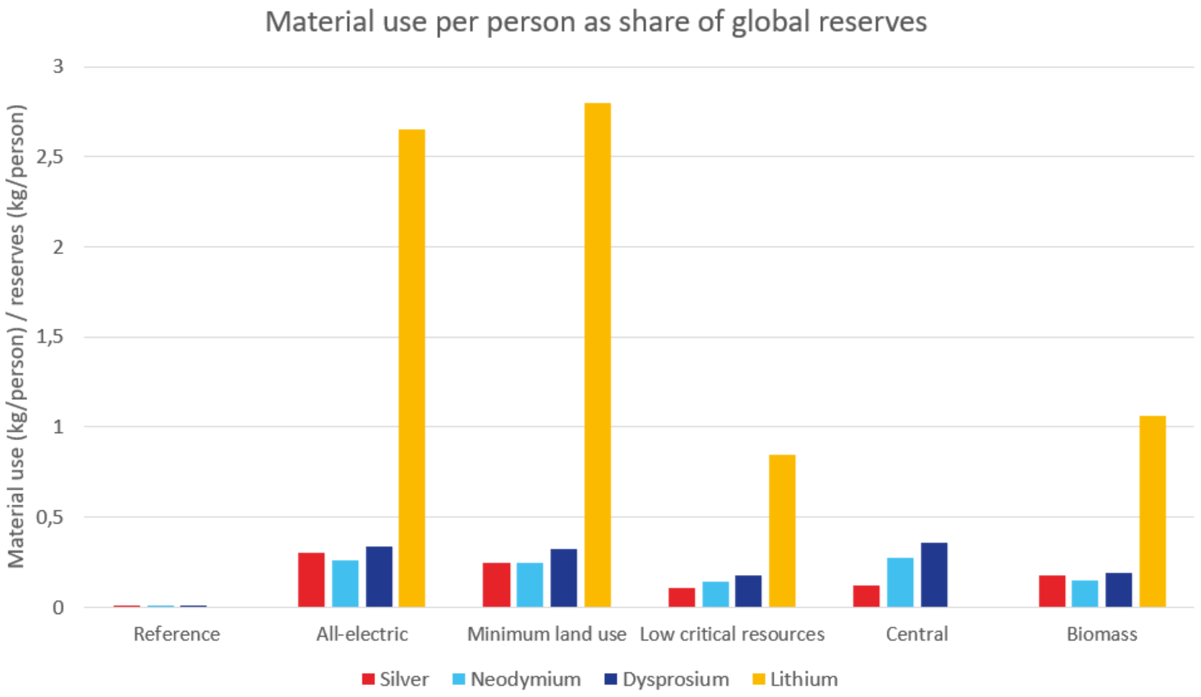


Figure 18 - Use of critical resources per person in each design, divided by the global reserves per person. It shows the resource use as share of reserves, both relative per capita. For the low/flexible energy demand.

What could, and probably will, decrease the critical resource requirement of the energy systems, is the fact that material use efficiency, as well as energy efficiency has increased over the past years (Grandell et al., 2016). If this continues, the same amount of energy can be produced with a smaller amount of critical resources. Another option that reduces the material requirement in relation to the global reserves, is the fact that the reserves could increase as a larger amount of the global resources become economically viable to extract from the earth. This could be the case due to higher prices of the critical resources, better and more efficient extraction technologies and when new resources/reserves are discovered (Giurco et al., 2019). Another solution that can solve the problem with critical resources are substitution materials that can be used to substitute the critical elements (Pavel et al., 2017a). In the situation as it is right now, an energy system without a need for critical resources is not likely. Therefore a balance need to be found in a trade-off between different technologies that use different types of critical resources. A solution could be, to use different technologies to meet the energy demand together. And within technologies, use different types of the technology or the same type with different critical elements if the performance is comparable. The table below shows an overview of the alternatives for the considered types of technologies, and potential substitution materials.

Table 16 - Alternatives for technologies that contain critical elements and potential substitutions for critical elements.

Solar PV	Silver in c-Si panels can be substituted by copper which is a less critical metal. It has a similar energy efficiency (Sinha and de Wild-Scholten, 2015).
	To reduce the amount of required c-Si PV modules, a share of alternative technologies can be used. Besides c-Si PV, a share of the demand could be provided by different PV types like CdTe and CIGS modules that are already commercially available.
Wind turbines	To date, no substitution elements of critical resources in NdFeB magnets are available. There is also no alternative magnet with similar properties (Pavel et al., 2017a). Lower performance magnets have been developed that can potentially replace NdFeB magnets in some applications making relatively more neodymium and dysprosium available for wind turbines (Pavel et al., 2017a).
	Except for the latest generation wind turbines, all existing wind turbines (77% of global capacity) uses conventional electromagnets based on steel and copper (Pavel et al., 2017a). Even though permanent magnets offer better efficiency, wind turbines with electromagnets still reach high capacities (Pyrhönen et al., 2010; Pavel et al., 2017a).
Li-ion batteries for grid electricity storage	There are alternatives for Li-ion batteries that can be applied on a large scale that have lower performances. The most mature alternatives are lead-acid, vanadium flow and sodium sulphur batteries (Zhang et al., 2018). These technologies have varying technical disadvantages compared to Li-ion batteries like a lower energy efficiency, lower energy density, long charging time and/or a high self-discharge rate (Zhang et al., 2018). Also newly developed batteries like aluminium-ion batteries are going to be a serious alternative. Even though the inferior performance, the alternatives can, an do to some extent, function as grid electricity storage batteries. If the different alternatives, that uses less critical resources could have a market share aside of Li-ion batteries, the criticality of lithium in energy supply on a larger scale would decrease.
(FC/B)EV	Chemistries that can substitute lithium (in) batteries have not been demonstrated yet at commercial level (Speirs et al., 2014). Other batteries like lead acid and sodium/nickel chloride batteries have been applied in vehicles, but the significant better energy density of lithium allows them to reach acceptable ranges (Speirs et al., 2014). Therefore it is not likely that other battery types are a logical substitute. By reducing the lithium requirement in Li-ion batteries, the total lithium requirement can be reduced (Speirs et al., 2014)
	Instead of a PSM motor that requires rare earth elements (like neodymium and dysprosium), there are alternative motor types like ASM and EESM motors (Pavel et al., 2017b). These are already available and commercially applied in BEVs but they have some disadvantages; lower efficiency in urban condition and lower power density (Pavel et al., 2017b). It could be a substitution for PSM motors for larger quantities than currently. Also a market share for FCEV would reduce the amount of required lithium (Speirs et al., 2014)

4.6.2 Resources

In the figure below, the same type of figure is presented as for the global reserves, but with global resources instead of reserves. Logically, the critical resources used for Haven-Stad, are a smaller share of the resources than of the reserves. All critical resources score below 1 for all designs, what means that the people in Haven-Stad do not use more of the critical resources for the energy supply in Haven-Stad, than their share would be if the global resources are allocated equal per capita. The value can decrease further if the resources increase due to the discovery of new resources. Another option to decrease the value is when the material use efficiency will increase, so when the same amount of energy can be generated/stored with a smaller amount of critical resources.

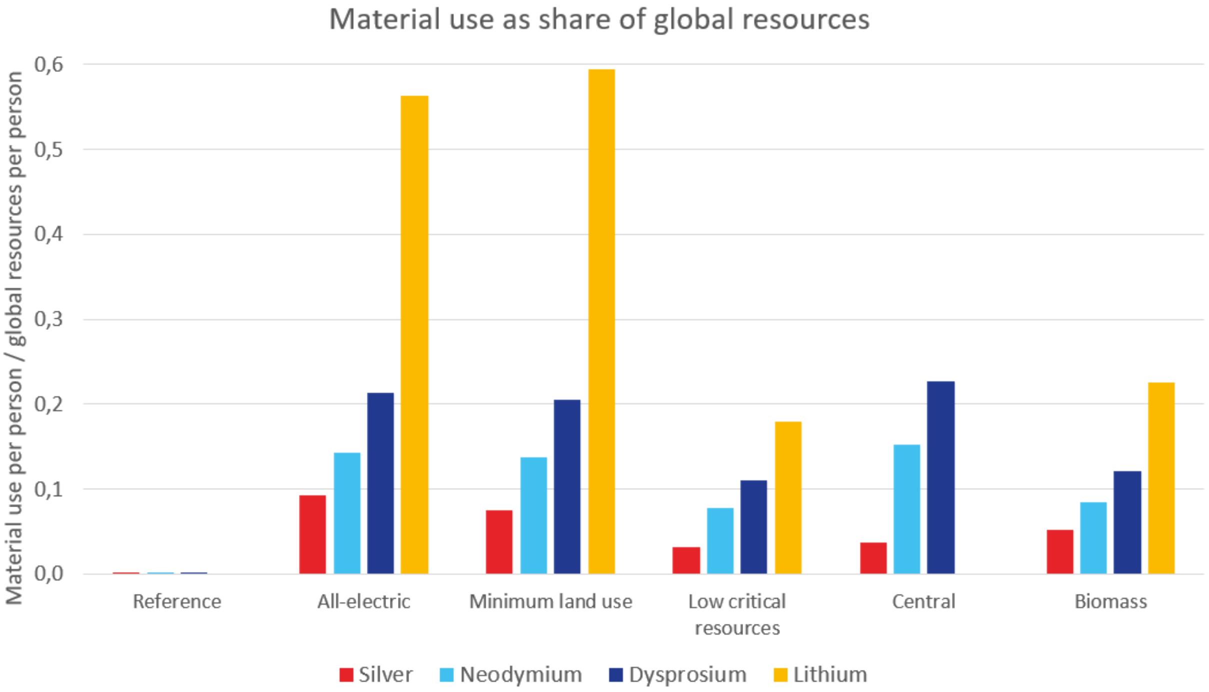


Figure 19 - Use of critical resources per person in each design divided by global resources per person. It shows the metal requirement as share of global resources, both relative per capita. For the low/flexible energy demand.

For lithium, the global resources are high in relation to the reserves, compared to the other critical metals. Therefore the relative lithium use in Haven-Stad is well below 1 in all renewable designs. Nevertheless, each system in which BEVs and/or battery storage are used, the lithium requirement per person is between 18 and 60% of the global resources per person, if allocated equal per capita.

This means that a higher percentage of the total lithium resources per person is required for BEVs and grid electricity storage than the current share of these technologies in the total lithium consumption. This is because a smaller share than 18-60% is currently used for energy system purposes because lithium is currently generally used in batteries in all kind of end uses. Currently, 65% of the global lithium is used for batteries, of which more than 50% is used for consumer electronics and only around 10% is used for grid energy storage systems (Varma, n.d.; USGS, 2020a). In the central design, with no battery electricity storage and no BEVs, there is no lithium requirement. This shows that lithium is not necessary within renewable energy systems. Looking at table 16, is can be seen that there are no alternatives for Li-ion batteries within vehicles with similar performance, but if not 100% of the vehicles is a BEV, but a particular share up to 50% is covered by FCEV, the lithium requirement for transport will reduce by maximum 50%. A market share of 50% for FCEVs can currently be achieved by the platinum industry without problems with the critical element in fuel cells (Pollet et al., 2012).

From figure 19 becomes clear that the neodymium and dysprosium requirement for Haven-Stad is roughly 10-20% of the global resources per person. This has potentially more consequences than for other critical elements as there is not a design that has no or very low neodymium and dysprosium requirement. Besides, for NdFeB magnets, there are no commercially available alternatives with comparable performance and there are also no substitution elements that could substitute for the critical elements (see table 16). As NdFeB magnets are used in wind turbines, BEVs and FCEVs, a system without or significant lower requirement for NdFeB magnets and its critical elements is not likely. Only in the situation that magnets with lower performance are accepted, the neodymium and dysprosium requirement could reduce. Another solution would be if non-energy related applications will switch to other magnets than NdFeB, so a higher share of NdFeB magnets will become available for energy related applications (Pavel et al., 2017a).

As the average amount of cars per household in Amsterdam is 0.4, the lithium, neodymium and dysprosium requirement is probably low compared to neighbourhoods in all other areas in the Netherlands since the amount of cars per household in Amsterdam is the lowest in the Netherlands (CBS, 2016a). So if these renewable designs were applied in other neighbourhoods outside Amsterdam, the requirement of critical elements per person is probably higher that for Haven-Stad, considering that the average amount of cars per household in the Netherlands is 0.9 (CBS, 2016a). Another important note is that the figures for reserves, resources and in the next section for annual production, are on the basis of the designs with low/flexible energy demand. With current average energy demand, the figures look similar but with slightly higher requirement of the critical elements. They are not shown as the low/flexible demand is more likely to occur since the neighbourhood need to be built yet, and because of the fact that it would make the figure less clear to read.

4.6.3 Annual production

In figure 20, the resource requirement for Haven-Stad is shown, as a percentage of the global annual production. The reserves and resources may be sufficient to meet the demand, but when the required amount of resources is not extracted from the earth, it cannot be used. Therefore it is important to look at annual production to see whether enough of the resources could be made available or not.

If the resource requirement for the energy system of Haven-Stad is 1% of the global annual production, 100 systems that are similar to the energy system of Haven-Stad could be achieved per year. This says something about the feasibility and scalability of the particular energy system (or elements in it). If 100 energy systems that are similar to Haven-Stad could be achieved per year, only 0.16% of the global population could are provided with such an energy system, assuming that all produced/extracted resources are used for energy systems what is not likely. This does not imply that it is not possible to produce the required amount, but that the annual production need to be scaled up if possible to implement similar energy systems (or elements in it) on a larger scale. It is not intended to pretend that these design should be scaled up and implemented at global scale because there is no singular energy system that fits the best for each energy system on earth. It is intended to give an indication whether the current production is adequate to supply sufficient resources that it could be assumed that the production will not constrain the shift from fossil fuels to renewable energy sources.

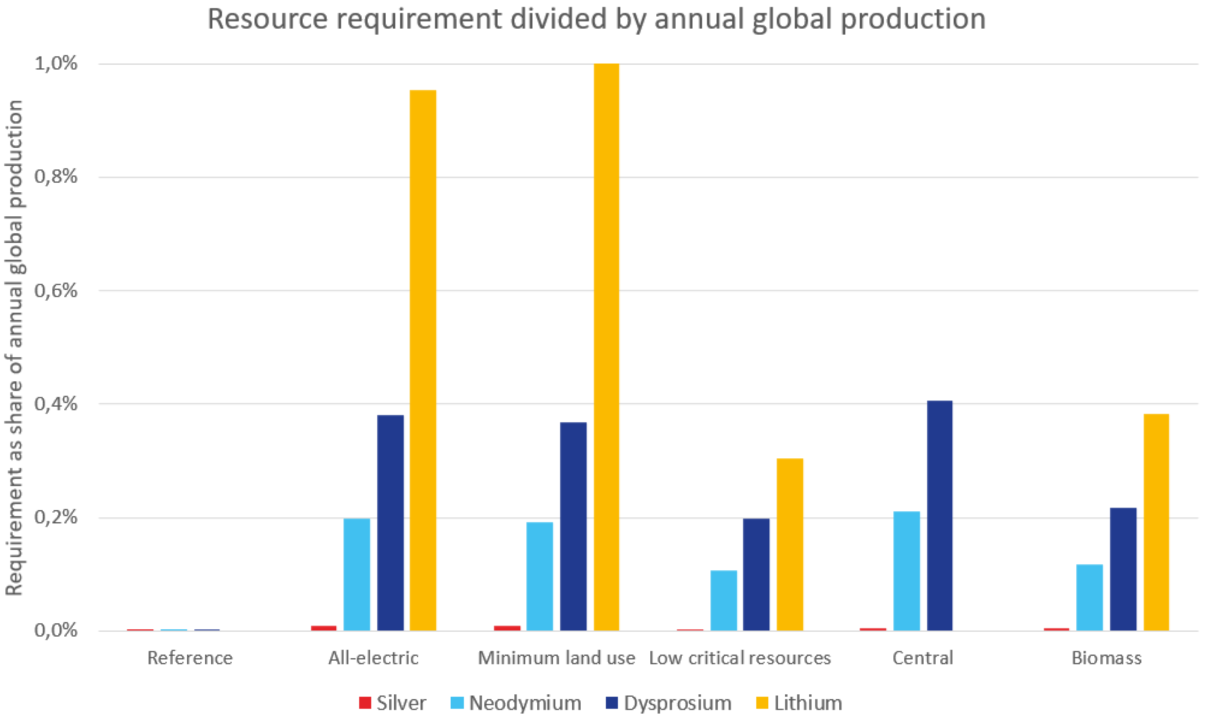


Figure 20 - The requirement of critical resources in the designs as a share of annual global production. With low/flexible energy demand.

Assuming the current share of PV in silver demand and the current annual silver production, there could be produced 88.7 GW of c-Si PV per year (see section 4.5.2). If these assumed values remain constant over the next decades, there could be installed 2661 GW of c-Si PV up to 2050. That corresponds to 0.34 kW/person with a global population 7.8 billion. In the renewable designs for Haven-Stad is 0.30 to 0.94 kW/person of PV installed. That shows that the current annual silver production and share of PV in the silver consumption is sufficient to implement the amount of c-Si PV in the low critical resources designs on global scale before 2050. To implement the amount of c-Si PV per person in the all-electric design on global scale before 2050, around 3 times more silver should be made available than is possible with the current annual silver production and share of PV in the silver consumption. The year 2050 is used as the ambition is to be carbon neutral in 2050 what implies that all energy systems need to be carbon neutral within 30 years (Klimaatakkoord, 2019).

Positive developments in PV technologies can avoid that problems occur with supply issues or silver depletion. As indicated in literature, the silver requirement per m² of c-Si cells has decreased from around 12 g/m² in 2010 to 1 g/m² that is expected for 2020 (Grandell et al., 2016). This occurs mainly due to substitution of silver by other metals but often the substitution metal can also be qualified as (potentially) critical (Grandell et al., 2016; Van Exter et al., 2018). Giurco et al. (2019) even argues that the material intensity will decrease to 4 t silver per GW what is only approximately 20% of the current silver use in PV. Increased efficiency will also decrease the material use per kWh of output. The energy yield of PV is dependent on the geographical location of the installation because the generation potential varies with the local irradiance (Kim et al., 2014; de Wild-Scholten, 2013). This means that the same PV module, with the same amount of critical resources, produces more electricity in regions with higher solar irradiance. Another option than can decrease problems with the supply of critical resources is when metals in lower concentration can also be mined in an economic viable way. However the extraction of most critical elements is only economical when it is available in concentration that are far above its average crustal abundance (Jean et al., 2015).

As for neodymium and dysprosium in NdFeB magnets no alternative is available with similar performance within EVs and wind turbines, it is important that sufficient neodymium and dysprosium could be made available in time. With the material use intensity and annual production that are shown in table 14 and 13, an indication could be given for whether the current annual production is enough or not. In the unrealistic situation that all produced neodymium and dysprosium is used only for EVs, it takes around 24 and 44 (respectively for neodymium and dysprosium) years to replace all 947 million personal cars on earth with BEVs or FCEVs (Statista, 2020), assuming that the current annual production remains equal. Taking into account that only 2% of the NdFeB magnets is currently used for electric vehicles (table 15), the current annual production is not sufficient to supply for the requirement amount of neodymium and dysprosium to produce enough EVs before 2050 without even considering the need of these metals for other applications. Therefore the annual production needs to increase significantly to make a sufficient amount available. Doing the same thing for lithium in BEV, it takes almost 100 years to replace 947 million cars by BEVs without considering other applications of lithium. Currently 65% of the lithium demand is used in batteries that are used in all kind of applications (USGS, 2020a). This imply that the lithium production per year need to increase in the coming years. Although the assumption that all personal cars are BEVs is not likely, the annual production is currently so low that it is not sufficient to reach the target for decarbonization of mobility before 2050. Apparently, the lithium production industry is capable of scaling up the production as the global production of lithium is currently approximately three times higher than in 2000 (Speirs et al., 2014). The global demand will approximately double up to 2025 and the share of (hybrid) EVs in the demand will increase to over 50% (Jimenez, 2018; Mernagh et al., 2013; Cohen, 2020). As there is no renewable design with neglectable or no requirement for neodymium and dysprosium, and there is currently no appropriate alternative for these elements in BEVs and FCEVs, these metals are considered as most critical. For lithium the same can be said as there is no substitution element with comparable performance for BEVs. This specific problem could be avoided if the demand for personal cars decreases over time. For example due to a shift to public transport or a lower demand for travelling in general.

It is assumed that all critical elements that are used in the energy systems can be recycled. So that the same amount of materials becomes available after the lifetime of the technologies in which they are used.

4.7 Location of the environment impact

Except for the magnitude of the environmental impacts, also the location of the impact is important, as well as the extent to which the impact is concentrated to a certain area. Therefore the location of the environmental impacts are mapped for the relevant sustainability indicators. Earlier in this report in the chapter about sustainability indicators, it is mentioned that eight sustainability indicators are relevant in the context of the current fossil fuel based energy systems: ‘global warming’ (GHG emissions), ‘ozone depletion’, ‘freshwater use’, ‘water quality/toxicity’, ‘terrestrial quality/toxicity’, ‘air quality/toxicity’, ‘rational use of resources/materials’, and ‘land use’. These indicators are important to consider for energy systems on the basis of fossil fuels, but as the exclusion of fossil fuels would reduce the impact of multiple indicators to manageable levels (see appendix A), only GHG emissions, land use and the use of critical resources were considered for 100% renewable energy systems in Haven-Stad. To determine the effect of the shift to 100% renewable energy systems with respect to the location of the environmental impact, also the impact of fossil fuel based energy systems are mapped. An estimation of this is shown in a schematic overview in the figure below. In this figure, all sustainability indicators for energy systems are incorporated because these are relevant in the context of fossil fuel based energy systems.

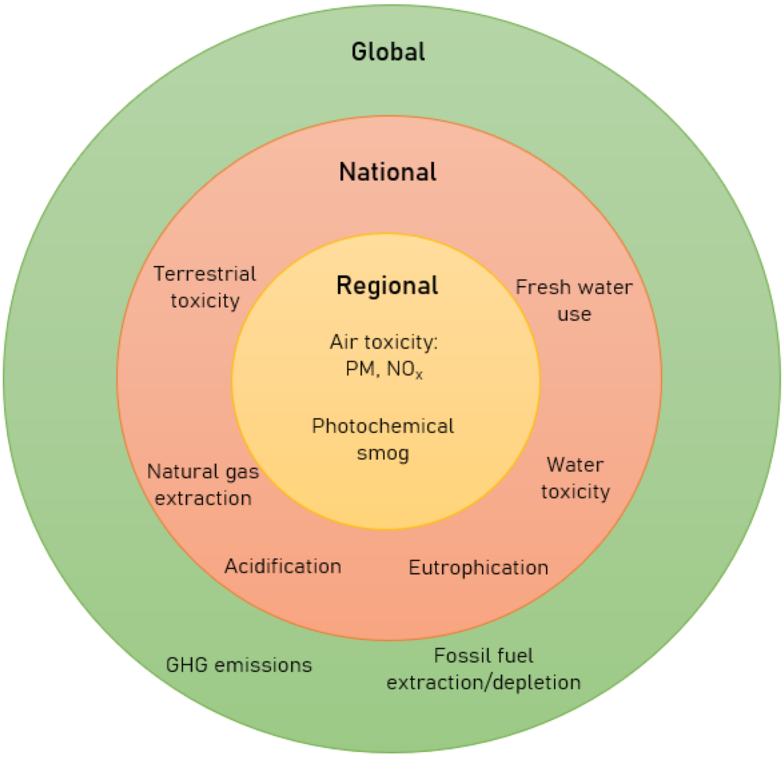


Figure 21 - The location of the environmental impact categories for fossil fuel based energy systems.

As can be seen in the figure, most of the indicators have their impact on regional or national level. This is because the environmental impact of energy production from fossil fuels is caused by the energy conversion step of burning fossil fuels what generally happens in the regions where the energy is consumed, resulting in local impact. In contrast to fossil fuel, the environmental impact of renewable energy sources can be attributed to the upstream and downstream activities since the energy conversion step is generally not (or to a small extent) related to environmental impact (Sathaye et al., 2011). As the upstream process of renewable energy technologies does generally not occur in Haven-Stad or the Netherland, but in other countries or continents, the environmental impact of renewable energy technologies is smaller in the Netherlands and relatively larger on international scale. The figure below shows an estimation of the scale on which each type of impact takes place.

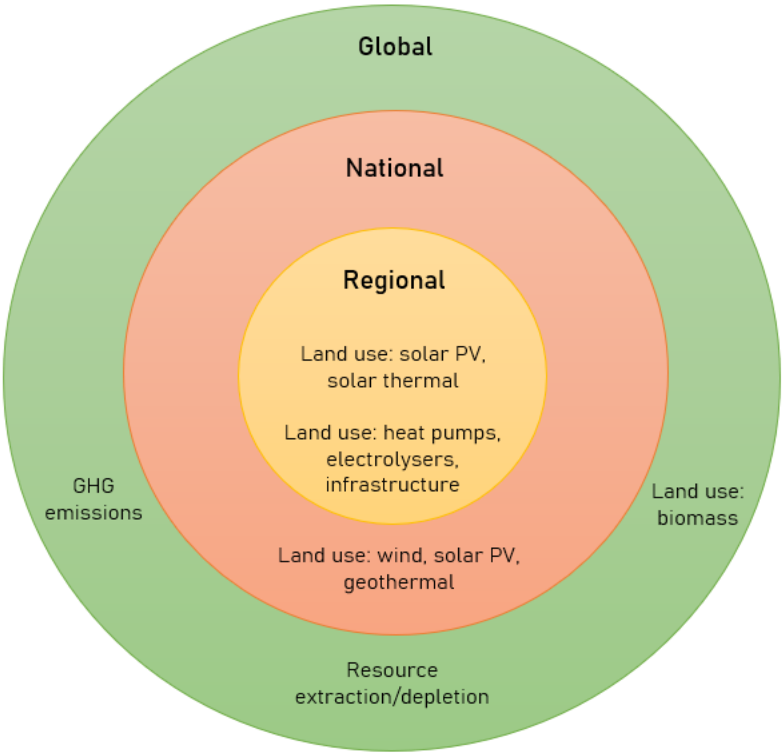


Figure 22 - The location of the environmental impact categories for 100% renewable local energy systems.

Where a lot of impacts in the current (fossil fuel based) energy systems causes problems at regional/national scale, the environmental impact of 100% renewable energy systems are generally on international scale. Also the type of impact changes with the shift to renewable energy; currently the main problem is global warming due to GHG emissions while this is a minor problem in renewable energy systems due to the exclusion of fossil fuels. In renewable energy systems, the main problems are the limited amount of required critical resources and land use, especially for biomass production. Biomass, as well as critical resources are produced/extracted in particular regions and distributed to the place where they are necessary to produce energy production or storage technologies, or to be used directly for energy production in the case of biomass (chips or pallets). Only for the final energy conversion step, they are transferred to the place where the energy will be consumed; in this case Haven-Stad.

Therefore, large scale renewable energy supply requires international agreements and regulations, even more than currently. This is due to the fact that the environmental impact does not take place at the place where the renewable energy is used. This can be considered as an unfair distribution of the positive and negative impacts. It is also important to consider the geographic concentration in which the impact takes place. The maximum amount of cropland according to the planetary boundary framework is a global maximum with the aim to prevent for land use change impact. But if a relatively small area in the world provides all biomass, it could cause a big impact on that region that cannot be considered as sustainable.

Chapter 5: Discussion

The primary motive for this study was that in existing literature, policies and regulations about the sustainability of energy systems is predominantly focussed on the reduction of GHG emissions. As the shift from fossil fuels to renewable alternative can result in negative impacts for other sustainability indicators (land use and use of critical resources), these are taken into account as well in this study. Another gap in literature was the fact that renewable energy sources are often compared to each other in LCAs, but generally the environmental impact was not compared to a sustainable reference value. As absolute limits will be needed to drive changes that are needed for the transition to a sustainable energy system, these are important to take into account. Besides, in existing literature, sustainable technologies or abstract scenarios are often compared to each other, instead of concrete designs for an entire energy system. This study takes these issues into account by comparing the different renewable energy sources to each other, as well as the designs, with respect to multiple sustainability indicators that are relevant in the context of 100% renewable energy systems. At last this study takes into account an appropriate scale of research by analysing at neighbourhood level within a national system instead of emission/energy neutrality for each household or an neighbourhood as energy autonomy. This is the right starting point because not every house or neighbourhood has to be energy neutral on its own as every house and neighbourhood is different, so 100% renewable energy production on national scale is more appropriate to assume. From an analysis on neighbourhood level, advices and implications for involved stakeholders can be composed in the best way since local authorities are supposed to play an important role in the realisation of the energy transition as they can find solutions that fit the local context more effectively than larger authorities (Kelly and Pollitt, 2011; Evola et al., 2016).

5.1 Interpretation of the results, implications and advices for stakeholders

By including the above mentioned perspectives, this study distinguishes itself from existing literature. The implications of the results, as well as how the results of the different chapters relate to each other is explained below, divided in different topics.

5.1.1 Interpretation of reference values

In the introduction and methodology is mentioned that literature indicates that absolute limits will be needed to drive change that is needed for the sustainable transition of energy systems (Meyer and Newman, 2020). Limits are often derived from global budgets and allocated to regions on the basis of population distribution, development rights or ability to pay (Lucas and Wilting, 2018). Globally, the budgets need to be taken into account but between regions the allocations of the budgets can be different. Not only on the basis of population, welfare or ability to pay, but also on the basis of regional circumstances. Budgets and limits should be assessed on a scale as large as possible. At global scale the budgets need to be achieved but not every region has to meet every budget that is equally divided over the global population. For example Denmark has a high potential for wind and a lower potential for solar PV. Therefore it should be able to use a higher share than ‘equal per capita’ of critical resources necessary for wind turbines and a smaller budget for solar PV related critical element. For an area in a desert it could work the other way around. However, the budgets do give an indication and guidance in a qualitative assessment of the environmental impact of energy systems. This is the intended use in this research instead of being strict limits.

5.1.2 Implications of the environmental impact of the designs

The primary motive for the transition to renewable energy is the reduction of GHG emissions to keep the global temperature increase manageable. Based on the results of this research can be said that the GHG emissions of no renewable design exceeds the global carbon budget if the budget is divided (cum.) equal per capita. As the sustainable reference values are exceeded frequently for the other consider environmental impacts, GHG emissions seem to cause the least problems of the three considered environmental impact categories. As the carbon budget for 2.0 °C is more than twice the budget for 1.5 °C temperature increase, it could be said on the basis of the results that it is realistic that the target of the Paris agreement will be met (stay well below 2.0 °C and strive for 1.5 °C). This imply that the shift from fossil fuels to renewable energy would decrease the GHG emissions of energy systems to levels where the consequences of global warming are manageable and that the focus could be shifted to other environmental impacts. This in contradiction with current global and national policies that focus nearly exclusively on the reduction of GHG emissions of energy systems (Kouloumpis et al., 2015). It might be better to focus on land use and the use of critical element regarding the sustainability of renewable energy sources as it is realistic the exclusion of fossil fuels would reduce the GHG emissions to acceptable levels.

Another thing that became clear from the results is that solar thermal and geothermal heat production seem to be ideal to implement in relation to the impact on GHG emissions, land use and use of critical resources because these impacts are low in relation to other energy sources. Also the use of hydrogen production for energy storage could be a good alternative for battery electricity storage because it does not require critical resources and due to the fact the lithium use is scarce. Besides, it could provide an alternative for Li-ion batteries and BEVs if hydrogen is used for FCEVs so it could reduce the use of lithium.

5.1.3 Share of intermittent and stable energy sources

From the results became clear that the share of intermittent energy sources (especially for electricity) in the energy production has implications for the different impacts. At first, designs with solely intermittent electricity production are not appreciated as it increases the need for electricity storage and the dependence on weather conditions. The only considered stable energy source within this research is biomass. The results have shown that biomass can cause negative GHG emissions and does not require critical resource, so if the amount of biomass stays within the limits of land use (on average not more than 385 m^2 of cropland for dedicated energy crops), biomass is a solution to incorporate a stable share without problematic environmental impact. This prevent for the necessity for high electricity storage capacities. As can be seen in the results, the designs with a high share of intermittent sources (all-electric and minimum land use) have a higher need for electricity storage in contrast to the designs with a high share of biomass.

The advice to use biomass within the boundaries for land use is in contradion with the current controversy about the use of bioenergy due to the questionable contribution to the reduction of environmental impact (Gamborg et al., 2012). Currently, there is no urgent need for renewable non-intermittent electricity sources, as long as fossil fuels are used. But as no renewable non-intermittent alternative is available, and large storage technologies without environmental impact are not mature enough or commercially available (e.g. hydrogen), it currently seems to be the only option within 100% renewable energy systems to provide non-intermittent electricity. If a storage technology without significant environmental impact will be available in the future, the need for non-intermittent sources would decrease as storage technologies could match the intermittent supply with the demand. In other region with a high potential for e.g. geothermal power or hydropower, these technologies could be an alternative.

Another result with respect to the share of intermittent energy production is that the impact of the inclusion of flexible energy demand has a larger positive effect on energy systems with a high share of intermittent sources. In all three impact categories, the reduced impact due to the inclusion of 10% flexible electricity demand is the highest for the design with only intermittent electricity production (all-electric). So it could be considered to implement/stimulate flexible energy demand to a larger extent if energy is supplied primarily by intermittent sources as this reduces the required installed capacity, electricity storage and corresponding GHG emissions, land use and use of critical resources.

As a share of stable energy production is preferred and biomass can cause problems with land use change, an interim solution in the transition to 100% renewable energy systems can be to incorporate a small share of natural gas that function as a flexible energy source that is only used if the intermittent sources are not sufficient. As natural gas has a high efficiency, is flexible, has the lowest emissions of the fossil fuels and can be used in combination with CCS, it could be used without significant environmental impact. This will reduce the need for biomass and storage techniques what will reduce the land requirement and use of critical resources within the system.

5.1.4 Trade-offs between the sustainability indicators

As explained in the method section, different energy systems have different impacts on varying sustainability indicators. A decarbonized energy system does not have lower impact on every other sustainability indicator. Therefore, there is looked at trade-offs between the different environmental impacts. At first the use of biomass causes an opposite effect on the indicators. It can cause negative GHG emissions and there are no critical element involved. On the other hand biomass is by far the primary contributor to land requirement. A second trade-off that goes along with the use of biomass is regarding the location of the land use impact. If the global total land use impact increases due to the use of imported biomass, the impact within the Netherlands decreases as less other energy source are needed. In densely populated regions/countries, imported biomass could be a solution as it does not require land within the region and at the same time it reduces the need for other energy sources that require land within the region like wind or solar PV. Biomass increases the global land use impact significantly but it reduces the land use impact at the location of bioenergy consumption if the biomass is imported.

Another type of trade-off is about the amount of electricity production in relation to direct heat production. With direct heat production from biomass, solar thermal and geothermal, no critical elements are involved but with electricity production and storage it does by wind turbines, solar PV and electricity storage. The use of heat pumps decreases the total primary energy use but increases the use of critical resources if the extra electricity for heat pumps is generated by PV and wind, or if more batteries are required. So it decreases the primary energy demand what result in lower GHG emissions and land use, but on the other hand the use of critical resources increases as more electricity is required.

The last identified trade-off is between battery electricity storage and hydrogen as energy storage. Batteries need critical resources while hydrogen production and use at al later moment has a lower efficiency than batteries. Thereby, it requires more electricity in total what result in higher primary energy use what could cause higher emissions, land use and probably extra use of critical elements.

5.1.5 Critical resources and transport

The use of particular elements becomes critical if the global reserves and resources are not sufficient to supply the required amount. Also a rapid demand increase can cause problems if the production rate is not sufficient. Especially if there are no serious alternatives or substitution materials for the critical elements, it could constrain the upscaling of renewable energy technologies. For the use of neodymium and dysprosium within BEVs, FCEVs and wind turbines is no alternative or substitution element with comparable performance. There is not per definition a shortage of these metals, but there is more required for energy systems than the share of the global consumption that is currently used for EVs and wind turbines. This implies that the share of wind turbines and EVs in the total demand for neodymium and dysprosium need to increase what could have consequences for other applications of the elements. Besides, the annual production has to increase significantly to make enough of the reserves/resources available for energy systems to make the transition to clean energy before 2050. It could be a solution to try to decrease the total demand for passenger cars. Or to work towards a higher market share of the 'Externally excited synchronous motor' (EESM) that is rare earth element free and is already used in the Renault Zoe (Pavel et al., 2017b). Lithium is another critical element for which is no alternative with similar energy density performance. For BEVs, FCEVs can be an alternative that use less/no lithium. Instead it require platinum that constrain them from being able to provide for a majority of the passenger cars.

Lithium is a critical resources that has also a lot of other applications than EVs and grid electricity storage. 65% of the lithium is used for batteries, and only 10% of these batteries are used for energy storage systems while 50% is used for consumer electronics (Varma, n.d; USGS, 2020a). The share of the energy system related applications in the global lithium demand has to increase to achieve the realisation of BEVs and battery grid electricity storage by Li-ion batteries on a large scale. Also the annual global production of lithium (as well as for neodymium and dysprosium) is not sufficient to replace all personal cars by BEVs (or FCEVs) before 2050, even without using any of the metals for other applications. This indicate that the annual production has to increase to achieve that. In general could be said that the distribution in share of the lithium use need to change and that it is advisable to be cautious in the use of lithium for grid electricity storage and EVs. Especially in densely populated urban areas it is advised to work towards a higher use of public transport and car sharing to save the scarce lithium for less densely populated areas where public transport and car sharing are less applicable.

With the share of c-Si PV modules in all renewable designs, there are no problems expected with the amount of silver that is used. This imply that c-Si PV modules can be produced at global scale and provide a similar share of energy as in the designs in this study, without problems regarding the silver use. Even if the share of silver use for PV in the global silver demand and the annual silver production remains equal, the installed solar PV per person could be applied globally before 2050 in the low critical resources and central design. For the other design, maximum three times as much silver is required what could be achieved by the expected reduction in silver use per m^2 PV, the substitution of silver by copper, an increase of silver production or if a larger share of the global silver production is used for PV. What should be considered are the geographical circumstances of energy systems as solar PV produces more electricity per m^2 in regions the solar irradiance is higher. So in southern Europe is the required area of solar PV for the same amount of energy production lower than in the Netherlands. Therefore it makes sense to implement a higher share of solar PV in regions with a higher solar irradiance.

For all considered critical elements is assumed that they can be recycles while this is in reality not yet the case. The results have shown that global upscaling of similar energy systems as the designs for Haven-Stad could be hindered by the amount of the resources that are (or could be made) available. The assumption of recycling of the resources is essential for the realisation of the transition to renewable energy systems and to ensure that components of the energy systems could be replaced after their lifetime. So it is recommended to focus on, and work towards a 100% recycling of the critical elements.

5.1.6 Implications of results that are specific for densely populated urban areas

A result that distinguishes a densely populated region like Haven-Stad from rural areas is that that the land requirement for the energy system is higher in relation to the surface area of the region where the energy is used. 5 to 19 times as much area is required to produce the energy than the surface area of Haven-Stad itself. At the same time, the energy that is generated in the direct vicinity of the neighbourhood is lower than for rural neighbourhoods/regions. This confirms that neighbourhoods should not be built and analysed as energy autonomy but energy demand and supply should be matched on a larger scale (e.g. national). Another difference is that there are less cars per households in densely populated regions. Even with the relatively small amount of cars, the lithium requirement is problematic if all cars are BEVs. In rural areas this problem of lithium requirement per capita would be even larger. In contrast to the suggested neighbourhood-oriented approach in the Dutch climate agreement, it could be argued that the implementation of renewable energy supply and corresponding environmental impact should be managed on a larger scale. The sum of best solutions for each specific neighbourhood is not inherently the best solution on national scale, so the energy system in neighbourhoods should be suitable for the energy system on a larger scale instead of considering only the local circumstances.

The fact that the results of this research are specific for densely populated new built urban neighbourhoods indicate that the results and conclusions are limited generalizable. The results and conclusions are general for densely populated new built urban neighbourhoods and if the same research method would be carried out for already existing neighbourhoods or neighbourhoods that are located in rural areas, the results and corresponding conclusions would differ from this research. This research only took the energy generation technologies into account that are applicable in the Netherlands, but in regions with a higher potential for e.g. geothermal or hydropower, the results would be different.

5.1.7 Location of the environmental impact

As in literature is indicated that most of the environmental footprints within the Netherlands remained constant since 1995, while the share of environmental impact abroad increases, the results in this study confirms what is earlier mention by Lucas and Wilting (2018); an externalization of environmental impact (Lucas and Wilting, 2018). A frequently mentioned motive for renewable energy is that it reduces the dependency on import of fuels (Cole and Banks, 2017). But due to an externalization of environmental impact due to renewable energy, it increases the need for global alignment to manage environmental impact. Therefore it affects the benefit of independent energy production as the impact in other countries need to be taken into account more. Another cause that decreases the independency of energy production is that critical elements that are required for renewable energy technologies are not distributed equally over the earth. Therefore countries could become dependent on the countries in which the resources are located. Just as currently with fossil fuels like oil and natural gas.

5.2 Limitations of the research

Even though the results are in line with the method and predominantly academic articles are used as data sources (no interviews or biased data sources), there are several limitation in this research that may have affected the results and decreases the reliability and validity of the research. At first, the environmental impact of Haven-Stad is composed on the basis of the use phase of the built environment and mobility by cars. As the future inhabitants of Haven-Stad will make use of other things and services that also affect the environmental impact categories, the environmental impacts (that are often shown per capita) could be seemingly too low and cause that the comparison with sustainable limit values is not one to one comparable. This limitation is considered in the interpretation of the results so the results and conclusion are not based on distorted information. Therefore this has not decreased the reliability of the results.

By mapping only the environmental impact of the energy system and comparing this to the total sustainable budget, an estimation need to be made to interpret the impact of the energy system for Haven-Stad in relation to the total sustainable budget and to what extent that is problematic. The environmental impact of other sectors is hard to estimate, especially with the assumption of 100% renewable energy, so no firm statements could be made about whether the budgets are going to be exceeded or not. Only about the contribution of the energy systems. This could be considered as a limitation but this was the intention on beforehand as only the energy system is relevant for Alliander for whom this study is performed and the available time was too short to analyse all sectors to map the impact in the whole country. Because the original intension was to see the contribution of the energy system to the sustainable reference values, the validity of the research has not been affected.

Besides developments in other sectors, also uncertainties is developments in technologies, potential substitution technologies/elements, increasing efficiencies, changing demands, divergent data for the same things in different sources and other uncertain variables could have had an effect on the results and the interpretation of the results. As there are endless uncertainties, they cannot be caught in designs or sensitivity analyses with the result that no firm statement could be made whether a certain sustainable reference value is going to be exceeded. Therefore only an indication is provided about the probability and what that implies for involved stakeholders. Also the reliability of the research could have been affected if data is used that deviates from the true values. To avoid that, multiple data sources are consulted for the same topic if varying and contradicting values were found. Besides, uncertainties are inherent to designing and analysing future scenarios as there are multiple plausible developments that cannot be predicted.

No sensitivity analysis is performed because a sensitivity is measured within the various designs and the two types of energy demand for which all the impacts of the designs are mapped. Given the large scale on which conclusions are drawn, without a focus on little details and differences in the designs/impacts, a sensitivity analysis is not considered as necessary.

Also in the modelling tool EnergyPLAN could be some irregularities that have affected the reliability of the outcomes but that could have been the case for each modelling tool. With EnergyPLAN, an argued decision is made for a tool that is suitable for this research (see section 3.6) and as the tool is also used for multiple peer reviewed articles (e.g. Mathiesen et al., 2015a; Mathiesen et al., 2015b; Child et al., 2017) it is assumed that the modelling tool has not caused a decreased reliability of the research.

5.3 Suggestions for further research

By doing the research, interpreting the results in the context of existing literature and looking at the limitations of the research, several relevant possibilities for further research have emerged. In line with what is earlier mentioned, it would be interesting to do the same research on national scale and incorporate the environmental impacts of all sectors what makes it possible to compare the impact of a country one to one with global budgets and limit values that are allocated to that particular country. By doing that, the effect of a 100% renewable energy system within a national system can be determined as the effect of renewable energy on the environmental impact of other sectors could be known as well.

In contrast to the suggestion of doing the study at a larger scope, it could also be relevant to zoom in on one aspect of this research. For example a critical resource that potentially cause problems. It could be relevant to look at alternatives for technologies that use these critical resources, or to see to what extend substitutions are available for the critical resources, or options for a more efficient use of the resources that reduce the required amount of it, and more of these in-depth topics.

Another potential direction for related research could be to look at the energy system of the same neighbourhood from a different perspective. For example from an architectural point of view to investigate how 100% renewable energy system designs should be implemented and built. Another perspective that could be relevant to investigate is to what extent the different renewable designs are feasible with respect to economic, social, political and technical aspects since this study exclusively focussed on sustainability within what is technically possible. Relevant aspect could be technical maturity, reliability, impact on quality of life, costs, contribution to the economy and social acceptance. This can show which aspects primarily prevent the renewable systems from being built from a practical and realistic point of view.

A thing that could be relevant to research is what specific design is the most suitable for a specific neighbourhood like Haven-Stad. In this report is only focussed on investigating the implications of the different design variations without the intention to determine which design is the best for Haven-Stad. To do that, the designs should be composed from another starting point. Now the designs are composed on the basis of one specific focus to see what that implies. The best design is probably somewhere in between the design.

Chapter 6: Conclusion

The aim of this thesis was to research the environmental impact of 100% renewable energy systems on neighbourhood level and to compare this impact to sustainable reference values in a broad sense. Also the trade-offs between these sustainability indicators in the context of 100% renewable energy systems were researched, as well as the effect of a different energy demand (pattern) and the location of the environmental impact categories for a 100% renewable energy system in comparison to fossil fuel based energy systems. This all is done to finally find out what are the implications of different renewable energy systems for stakeholders that are involved in the transition to renewable energy like municipalities, national government and real estate developers.

A broad set of sustainability indicators is assessed that is generally considered relevant in the context of energy systems. Due to the exclusion of fossil fuels, only GHG emissions, land use and the use of critical resources remain relevant for 100% renewable energy sources within the scope of this research. The impact on these indicators is analysed for the designs of the energy systems of Haven-Stad and qualitatively assessed in relation to sustainable reference values. These reference values are based on the carbon budget for 1.5 °C, a maximum amount of cropland for dedicated energy crops (based on planetary boundary framework) and the global resources, reserves and annual production of critical elements that are used in the renewable energy systems.

The results have shown that the shift from fossil fuels to renewable energy would decrease the GHG emissions of energy systems to levels where the consequences of global warming are manageable and that the focus could be shifted to other environmental impacts. Looking at the impact of different energy sources, it can be seen that solar thermal and geothermal heat production can be implemented without significant environmental impact in each considered impact category. From a sustainability point of view these are advisable to implement. The same could be said for biomass as long as it stays within the sustainable boundaries for land use for dedicated energy crops (on average approximately 385 m^2/person). Biomass has the highest land use intensity of all energy sources, but on the other hand it could cause negative GHG emissions (with CCS) and no critical elements are involved. Another benefit of biomass is that it is a non-intermittent energy source. An energy system with only intermittent energy sources is not recommended because it increases the need for energy storage what goes along with the use of critical elements, just as energy production from intermittent energy sources by solar PV and wind turbines.

In line with the share of intermittent sources, the inclusion of flexible electricity demand has a higher positive effect if a system has a higher share of intermittent electricity sources. The relative reduction of environmental impacts due to inclusion of flexible energy demand is the highest in the design with exclusively intermittent electricity production. This imply that implementing and stimulating flexible energy demand might be considered more seriously if a higher share of intermittent sources is installed.

In contrast to electricity production, direct heat production do not involve any critical resources. Heat pumps use electricity to produce heat with a COP of around 3.5 (Fischer and Madani, 2017). Therefore they reduce the primary energy demand what result in lower GHG emissions and land use, but on the other hand the use of critical resources increases as more electricity (and probably storage) is required due to the increased electricity need. The same could be said for electric heating which has a lower efficiency than heat pumps, making it a less suitable option but it can be used to manage excess electricity production. A similar trade-off is between energy storage using batteries or with hydrogen production and use on a later moment. Batteries need critical resources while hydrogen production and consumption has a lower efficiency than batteries. Therefore, the use of hydrogen requires more electricity in total, resulting in higher primary energy use what could cause higher emissions, land use and probably some extra use of critical elements. Because these two options cause different impacts, it is recommended not to strive for an exclusive use of one of the two options, but make the trade-off per energy systems on the basis of the local/national circumstances.

Regarding the use of critical resources, the requirement of neodymium, dysprosium and lithium within the designs will probably cause that there is not enough of these element to apply similar energy systems at global scale. Also because there are no alternatives/substitutions for these elements with comparable performance. It will cause that the share of energy-related applications of these elements in the total consumption of these elements need to increase as more is required in the renewable energy systems than their current share in the demand. There will be relatively less available for other applications of these elements. Therefore it is recommended to be cautious in the use of lithium for grid electricity storage and EVs. Especially in densely populated urban areas it is advised to work towards a higher use of public transport and car sharing to save the scarce lithium for less densely populated areas where public transport and car sharing are less applicable. Also stimulating a share of FCEVs could be considered as BEVs could not cover the whole passenger cars demand due to the lithium requirement. Besides, the annual production for lithium, neodymium and dysprosium has to increase significantly to make enough of the resources available for energy systems to make the transition to clean energy before 2050. All results are based on the current material use intensity of the critical elements in the technologies in which they are uses. But as it is likely that the material use intensity decreases in the future, the criticality of the elements would decrease as well. To achieve long term sustainable renewable energy systems, it is essential that critical resources are recycled or reused. This is currently not happening for 100% but without recycling, renewable energy systems as discussed in this research are not sustainable in the long term.

In densely populated areas, there are less cars per person than in other regions and even for this neighbourhood, the lithium requirement per person for cars (if all are BEVs) is as high as the global reserves per person. This increases the urgency for a lower demand for passenger cars or an alternative for lithium within EVs, or within other sectors what would make more lithium available for EVs. Another result that is specific for densely populated areas is that the land requirement for energy production in the different design is 5 to 19 times higher than the area where the energy is consumed; Haven-Stad. For rural areas this number would be lower, just as the proportion of energy that is produced in the direct vicinity. This emphasizes that the energy system of neighbourhoods should be considered as a part of the national energy system as densely populated areas do not have enough land available to provide for their own energy demand. So a neighbourhood-oriented approach is the best suitable scale for the implementation of energy and planning actions in sustainable city planning (Klimaatakkoord, 2019; Evola et al., 2016), but as not every neighbourhood can provide for their demand, the energy supply and demand should be matched on a larger (at least national) scale. Within the proposed neighbourhood oriented approach in the climate agreement, the suitability within the larger energy system should be taken into account as the whole of best solutions for local energy systems is not by definition the best solution on national scale.

In line with the location of the impact, an increased global land use impact due to the use of biomass, decreases the land use impact within the Netherlands if all biomass is imported. In densely populated regions/countries, (imported) biomass could be a solution as it does not require many land within the region and at the same time it reduces the need for other energy sources that require land within the region like wind or solar PV. This indicate that that the use of imported biomass increases the global land use impact significantly while it decreases the land use impact on the location where the bioenergy is used.

The location of the environmental impact shifts from the location where the energy is used (regional/national) to global impacts due to the shift from fossil fuels to renewable energy sources. Due to the externalization of the impact, the need for even more international agreements and regulations increases. A frequently mentioned motive for renewable energy is that it reduces the dependency on import of fuels (Cole and Banks, 2017). But due to the increased need for global alignment to manage environmental impact, the benefit of independent energy production diminishes as the impact in other countries need to be taken into account more. Besides, the required critical resources are also concentrated at particular places on the earth what could cause dependency on these countries.

References

Aas, W., Mortier, A., Bowersox, V., Cherian, R., Faluvegi, G., Fagerli, H., ... & Myhre, C. L. (2019). Global and regional trends of atmospheric sulfur. *Scientific reports*, *9*(1), 1-11.

Ala-Juusela, M., Crosbie, T., & Hukkalainen, M. (2016). Defining and operationalising the concept of an energy positive neighbourhood. Energy Conversion and Management, 125, 133-140.

Alexander, C., Litosh, S., Alway, B., Litosh, S., Wiebe, J., Yao, W., Saha, D., Norton, K., Li, S., Guy, F., Scott-Gray, N. & Goenka, S. (2019). World Silver Survey 2019. The Silver Institute: Washinton, DC, USA.

Amponsah, N. Y., Troldborg, M., Kington, B., Aalders, I., & Hough, R. L. (2014). Greenhouse gas emissions from renewable energy sources: A review of lifecycle considerations. Renewable and Sustainable Energy Reviews, 39, 461-475.

Ang, B. W., & Su, B. (2016). Carbon emission intensity in electricity production: A global analysis. Energy Policy, 94, 56-63.

Asdrubali, F., Baldinelli, G., D'Alessandro, F., & Scrucca, F. (2015). Life cycle assessment of electricity production from renewable energies: Review and results harmonization. *Renewable and Sustainable Energy Reviews*, *42*, 1113-1122.

Atilgan, B., & Azapagic, A. (2016a). Assessing the environmental sustainability of electricity generation in Turkey on a life cycle basis. *Energies*, *9*(1), 31.

Atilgan, B., & Azapagic, A. (2016b). Renewable electricity in Turkey: Life cycle environmental impacts. *Renewable Energy*, *89*, 649-657.

Beaudin, M., Zareipour, H., Schellenberg, A., & Rosehart, W. (2014). Energy storage for mitigating the variability of renewable electricity sources. *Energy Storage Smart Grids Plan. Oper. Renew. Var. Energy Resour*, *14*(4), 1-33.

Boccard, N. (2009). Capacity factor of wind power realized values vs. estimates. *energy policy*, *37*(7), 2679-2688.

Boehmel, C., Lewandowski, I., & Claupein, W. (2008). Comparing annual and perennial energy cropping systems with different management intensities. *Agricultural systems*, *96*(1-3), 224-236.

Bonamente, E., Pelliccia, L., Merico, M. C., Rinaldi, S., & Petrozzi, A. (2015). The multifunctional environmental energy tower: Carbon footprint and land use analysis of an integrated renewable Energy plant. *Sustainability*, *7*(10), 13564-13584.

Bringault, A., Eisermann, M., Lacassagne, S., & Fauchadour, N. (2016). Cities heading towards 100% renewable energy by controlling their consumption. Food for thought and action. Réseau Action Climat, CLER and Energy Cities. France.

Bronicki, L. Y. (Ed.). (2018). *Power Stations Using Locally Available Energy Sources: A Volume in the Encyclopedia of Sustainability Science and Technology Series*. Springer.

Brooks, D. B. (2015). *Supply and competition in minor metals*. Routledge.

Campbell, J. E., Lobell, D. B., Genova, R. C., & Field, C. B. (2008). The global potential of bioenergy on abandoned agriculture lands. *Environmental science & technology*, *42*(15), 5791-5794.

CBS (Central Bureau voor de Statistiek) (2016a). Veel auto's in grote steden ondanks laag autobezit. Retrieved 28-06-2020, from https://www.cbs.nl/nl-nl/nieuws/2016/49/veel-auto-s-in-grote-steden-ondanks-laag-autobezit

CBS (Central Bureau voor de Statistiek) (2016b). Kleine en nieuwere overheidskantoren verbruiken meer energie. Retrieved 04-06-2020, from https://www.cbs.nl/nl-nl/nieuws/2016/10/kleine-en-nieuwere-overheidskantoren-verbruiken-meer-energie

CBS (Centraal Bureau voor de Statistiek) (2018a). Bodemgebruik; uitgebreide gebruiksvorm, per gemeente. StatLine. Retrieved 01-06-2020, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70262ned/table?fromstatweb

CBS (Centraal Bureau voor de Statistiek (2018b). Energieverbruik van particuliere huishoudens. Retrieved 13-07-2020, from https://www.cbs.nl/nl-nl/achtergrond/2018/14/energieverbruik-van-particuliere-huishoudens

CBS (Centraal Bureau voor de Statistiek (2019a). Aandeel hernieuwbare energie naar 7,4 procent. Retrieved 14-04-2020, from https://www.cbs.nl/nl-nl/nieuws/2019/22/aandeel-hernieuwbare-energie-naar-7-4-procent.

CBS (Central Bureau voor de Statistiek) (2019b). Personenautoverbruik. Retrieved 28-06-2020, from https://www.cbs.nl/nl-nl/maatschappij/verkeer-en-vervoer/transport-en-mobiliteit/mobiliteit/verkeer/categorie-verkeer/personenautoverkeer

CBS (Central Bureau voor de Statistiek) (2020a). Rendementen en CO_2-emissie elektriciteitsproductie 2018. Retrieved 12-04-2020, from https://www.cbs.nl/nl-nl/maatwerk/2020/08/rendement-en-co2-emissie-elekrtriciteitproductie-2018.

CBS (Central Bureau voor de Statistiek) (2020b). Bevolking groeit naar ruim 17,4 miljoen inwoners. Retrieved 26-05-2020, from https://www.cbs.nl/nl-nl/nieuws/2020/01/bevolking-groeit-naar-ruim-17-4-miljoen-inwoners

CBS (Central Bureau voor de Statistiek) (2020c). Energieverbruik particuliere woningen; woningtype en regio's. Retrieved 04-06-2020, from https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81528NED/table?fromstatweb

CBS (Central Bureau voor de Statistiek) (n.d.). Welke sectoren stoten broeikasgassen uit? Retrieved 06-08-2020, from https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/hoofdcategorieen/welke-sectoren-stoten-broeikasgassen-uit-

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S. (2009). Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, conservation and recycling*, *53*(8), 434-447.

Child, M., Nordling, A., & Breyer, C. (2017). Scenarios for a sustainable energy system in the Åland Islands in 2030. Energy conversion and management, 137, 49-60.

Chu, S. (2011). *Critical materials strategy*. DIANE Publishing.

CLO (Compendium voor de leefomgeving) (2018). Verzuring en grootschalige luchtverontreiniging: emissies, 1990 – 2016. Retrieved 18-04-2020, from https://www.clo.nl/indicatoren/nl018324-verzuring-en-grootschalige-luchtverontreiniging-emissies

CLO (Compendium voor de leefomgeving) (2019). Energieverbruik per sector, 1990-2018. Retrieved 31-08-2020, from https://www.clo.nl/indicatoren/nl0052-energieverbruik-per-sector

Cohen, A. (2020). Manufacturers Are Struggling To Supply Electric Vehicles With Batteries. Retrieved 26-05-2020, from https://www.forbes.com/sites/arielcohen/2020/03/25/manufacturers-are-struggling-to-supply-electric-vehicles-with-batteries/#21af7db91ff3

Cole, P., & Banks, G. (2017). Renewable energy programmes in the South Pacific–Are these a solution to dependency?. *Energy Policy*, *110*, 500-508.

Conley, D. J., Paerl, H. W., Howarth, R. W., Boesch, D. F., Seitzinger, S. P., Havens, K. E., ... & Likens, G. E. (2009). Controlling eutrophication: nitrogen and phosphorus.

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied energy, 87(4), 1059-1082.

Corneau, S. (2018). Minerals in the Green Economy: Solar panels and lithium-ion batteries. Retrieved 18-05-2020, from https://www.igfmining.org/minerals-green-economy-solar-panels-lithium-ion-batteries/

Cornelissen, S., Koper, M., & Deng, Y. Y. (2012). The role of bioenergy in a fully sustainable global energy system. *Biomass and Bioenergy*, *41*, 21-33.

Crock, W. D. (2016). Mapping stocks and flows of neodymium: An assessment of neodymium production and consumption in the Netherlands in 2010 and 2030.

Dahiya, S., & Myllyvirta, L. (2019). Global SO2 emission hotspot database, Ranking of the world's worst sources of SO2 pollution. *Greenpeace Environment Trust*.

De Castro, C., Mediavilla, M., Miguel, L. J., & Frechoso, F. (2013). Global solar electric potential: A review of their technical and sustainable limits. *Renewable and Sustainable Energy Reviews*, *28*, 824-835.

De Wild-Scholten, M. M. (2013). Energy payback time and carbon footprint of commercial photovoltaic systems. *Solar Energy Materials and Solar Cells*, *119*, 296-305.

Dodds, P. E., Staffell, I., Hawkes, A. D., Li, F., Grünewald, P., McDowall, W., & Ekins, P. (2015). Hydrogen and fuel cell technologies for heating: A review. *International journal of hydrogen energy*, *40*(5), 2065-2083.

Dones, R., Heck, T., & Hirschberg, S. (2004). *Greenhouse gas emissions from energy systems: comparison and overview* (No. CH--0401).

Duleep, G., van Essen, H., Kampman, B., & Grünig, M. (2011). Impacts of electric vehicles, Deliverable 2, Assessment of electric vehicle and battery technology. *Delft, CE Delft*.

EEA (European Environmental Agency) (2014). Air pollution fact sheet 2014, Netherlands.

EPA (Environmental Protection Agency) (n.d.). Lifecycle Greenhouse Gas Results. Retrieved 01-07-2020, from https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results

European Commission (2015). Report on critical raw materials for the EU. Critical raw materials profiles. Ares(2015)1819595 - 29/04/2015.

European Commission (2016). Directive (EU) 2016/2284 of the European Parliament and of the Council of 14 December 2016 on the reduction of national emissions of certain atmospheric pollutants, amending Directive 2003/35/EC and repealing Directive 2001/81/EC. *OJL*, *344*, 1-31.

European Commission. (2017). Emissions of acidifying gases decreasing in the EU. Retrieved 14-04-2020, from https://ec.europa.eu/eurostat/web/products-eurostat-news/-/EDN-20170602-1.

European Commission (2019). NEC-programma NL. Retrieved 18-04-2020, from https://ec.europa.eu/environment/air/pdf/reduction_napcp/Netherlands%20Final%20NAPCP%201Apr.pdf

Evans, A., Strezov, V., & Evans, T. J. (2009). Assessment of sustainability indicators for renewable energy technologies. *Renewable and sustainable energy reviews*, *13*(5), 1082-1088.

Evans, A., Strezov, V., & Evans, T. (2010). Comparing the sustainability parameters of renewable, nuclear and fossil fuel electricity generation technologies. In *World Energy Council for Sustainable Energy, Congress Papers, Montréal 2010* (Vol. 27, p. 2011).

Evola, G., Fichera, A., Gagliano, A., Marletta, L., Nocera, F., Pagano, A., & Palermo, V. (2016). Application of a mapping tool to plan energy saving at a neighborhood scale. *Energy Procedia*, *101*(September), 137-144.

Evuti, A. M. (2013). A synopsis on biogenic and anthropogenic volatile organic compounds emissions: hazards and control. *Int. J. Eng*, *2*(5), 145.

Field, C. B., Campbell, J. E., & Lobell, D. B. (2008). Biomass energy: the scale of the potential resource. *Trends in ecology & evolution*, *23*(2), 65-72.

Fischer, D., & Madani, H. (2017). On heat pumps in smart grids: A review. *Renewable and Sustainable Energy Reviews*, *70*, 342-357.

Fizaine, F., & Court, V. (2015). Renewable electricity producing technologies and metal depletion: A sensitivity analysis using the EROI. *Ecological Economics*, *110*, 106-118.

Fritsche, U. R., Berndes, G., Cowie, A. L., Dale, V. H., Kline, K. L., Johnson, F. X., Langeveld, H., Sharma, N., Watson, H. and Woods, J. (2017). Global Land Outlook. Energy and land use. UNCCD and IRENA.

Fthenakis, V., & Kim, H. C. (2009). Land use and electricity generation: A life-cycle analysis. *Renewable and Sustainable Energy Reviews*, *13*(6-7), 1465-1474.

Gaines, L., & Nelson, P. (2009). Lithium-ion batteries: possible materials issues. In *13th international battery materials recycling seminar and exhibit, Broward County Convention Center, Fort Lauderdale, Florida* (p. 16).

Gamborg, C., Millar, K., Shortall, O., & Sandøe, P. (2012). Bioenergy and land use: framing the ethical debate. *Journal of agricultural and environmental ethics*, *25*(6), 909-925.

Geddes, J. A., & Martin, R. V. (2017). Global deposition of total reactive nitrogen oxides from 1996 to 2014 constrained with satellite observations of NO 2 columns. *Atmospheric Chemistry and Physics*, *17*(16), 10071.

Gemeente Amsterdam (2017). Haven-Stad, transformatie van 12 deelgebieden. Concept ontwikkelingsstrategie. Amsterdam.

Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, X., & Melin, S. (2011). Particulate matter emissions from combustion of wood in district heating applications. *Renewable and Sustainable Energy Reviews*, *15*(6), 3019-3028.

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. Renewable and Sustainable Energy Reviews, 76, 1283-1290.

Gieseke, R., Gütschow, J., & Nicholls, Z. (2019). Global Emissions Timeseries.

Giurco, D., Dominish, E., Florin, N., Watari, T., & McLellan, B. (2019). Requirements for minerals and metals for 100% renewable scenarios. In *Achieving the Paris Climate Agreement Goals* (pp. 437-457). Springer, Cham.

Goodland, R. (2002). Sustainability: human, social, economic and environmental. *Encyclopedia of global environmental change*, *5*, 481-491.

Grandell, L., Lehtilä, A., Kivinen, M., Koljonen, T., Kihlman, S., & Lauri, L. S. (2016). Role of critical metals in the future markets of clean energy technologies. *Renewable Energy*, *95*, 53-62.

Gujba, H., Mulugetta, Y., & Azapagic, A. (2011). Power generation scenarios for Nigeria: An environmental and cost assessment. Energy Policy, 39(2), 968-980.

Hare, W. L. (2012). A safe landing for the climate. In State of the World 2009 (pp. 39-55). Routledge.

Harvey, L. D. (2010). *Energy and the new reality 2: carbon-free energy supply*. Routledge.

Hebenstreit, B., Schnetzinger, R., Ohnmacht, R., Höftberger, E., & Haslinger, W. (2011). Efficiency optimization of biomass boilers by a combined condensation-heat pump-system. *Proceedings of ECOS*, 1465-1477.

Hegglin, M. I., Fahey, D. W., McFarland, M., Montzka, S. A., & Nash, E. R. (2015). *Twenty Questions and Answers About the Ozone Layer: 2014 Update-Scientific Assessment of Ozone Depletion: 2014*.

Henry, R. C., Engström, K., Olin, S., Alexander, P., Arneth, A., & Rounsevell, M. D. A. (2018). Food supply and bioenergy production within the global cropland planetary boundary. *PloS one*, *13*(3).

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., ... & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences*, *112*(20), 6277-6282.

Hettinga, S., Nijkamp, P., & Scholten, H. (2018). A multi-stakeholder decision support system for local neighbourhood energy planning. Energy Policy, 116, 277-288.

Hoenderdaal, S., Espinoza, L. T., Marscheider-Weidemann, F., & Graus, W. (2013). Can a dysprosium shortage threaten green energy technologies?. *Energy*, *49*, 344-355.

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., ... & Bond, T. C. (2018). Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development (Online)*, *11*(PNNL-SA-123932).

Horner, R. M., & Clark, C. E. (2013). Characterizing variability and reducing uncertainty in estimates of solar land use energy intensity. *Renewable and Sustainable Energy Reviews*, *23*, 129-137.

Hydro-Québec (2014). Technical report comparing power generation options and electricity mixes. Hydro-Québec Unité environnement et développement durable Direction principale - Environnement et Affaires corporatives 75 boul.

IEA (International Energy Agency) (2012). World Energy Outlook 2012. Paris, OECD/IEA. http://www.worldenergyoutlook.org/

IEA (International Energy Agency) (2019). World Energy Outlook 2019. Paris, OECD/IEA. http://www.worldenergyoutlook.org/

IPCC (Intergovernmental Panel on Climate Change). (2019). Climate change and land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. Summary for Policymakers.

Jacobson, M. Z. (2009). Review of solutions to global warming, air pollution, and energy security. *Energy & Environmental Science*, *2*(2), 148-173.

Jean, J., Brown, P. R., Jaffe, R. L., Buonassisi, T., & Bulović, V. (2015). Pathways for solar photovoltaics. *Energy & Environmental Science*, *8*(4), 1200-1219.

Jimenez, D. (2018). Lithium market outlook. SQM. Retrieved 26-05-2020, from http://s1.q4cdn.com/793210788/files/doc_news/2018/6/Foro-del-Litio-2018-Lithium-Market-Update-20180808-FINAL.pdf

Kaldellis, J. K., & Apostolou, D. (2017). Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart. *Renewable Energy*, *108*, 72-84.

Kato, E., & Yamagata, Y. (2014). BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. *Earth's Future*, *2*(9), 421-439.

Kelly, S., & Pollitt, M. G. (2011). 10 The local dimension of energy. *The Future of Electricity Demand: Customers, Citizens and Loads*, *69*, 249.

Kim, H., Cha, K., Fthenakis, V. M., Sinha, P., & Hur, T. (2014). Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems. *Solar Energy*, *103*, 78-88.

Klaassen, E., Frunt, J., & Slootweg, H. (2015). Assessing the impact of distributed energy resources on lv grids using practical measurements. In *23rd International conference on electricity distribution (CIRED)* (Vol. 2015, p. 5).

Klimaatakkoord (2019). *Klimaatakkoord.* Den Haag. https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

Knutti, R., Rogelj, J., Sedláček, J., & Fischer, E. M. (2016). A scientific critique of the two-degree climate change target. Nature Geoscience, 9(1), 13.

Kouloumpis, V., Stamford, L., & Azapagic, A. (2015). Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts?. *Sustainable Production and Consumption*, *1*, 1-21.

Kowalski, K., Stagl, S., Madlener, R., & Omann, I. (2009). Sustainable energy futures: Methodological challenges in combining scenarios and participatory multi-criteria analysis. *European Journal of Operational Research*, *197*(3), 1063-1074.

Kulig, B., Gacek, E., Wojciechowski, R., Oleksy, A., Kołodziejczyk, M., Szewczyk, W., & Klimek-Kopyra, A. (2019). Biomass yield and energy efficiency of willow depending on cultivar, harvesting frequency and planting density. *Plant, Soil and Environment*, *65*(8), 377-386.

Kumar, S. S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis–A review. *Materials Science for Energy Technologies*, *2*(3), 442-454.

La Rovere, E. L., Soares, J. B., Oliveira, L. B., & Lauria, T. (2010). Sustainable expansion of electricity sector: Sustainability indicators as an instrument to support decision making. *Renewable and Sustainable Energy Reviews*, *14*(1), 422-429.

Leader, A., Gaustad, G., & Babbitt, C. (2019). The effect of critical material prices on the competitiveness of clean energy technologies. *Materials for Renewable and Sustainable Energy*, *8*(2), 8.

Lieberei, J., & Gheewala, S. H. (2017). Resource depletion assessment of renewable electricity generation technologies—comparison of life cycle impact assessment methods with focus on mineral resources. *The International Journal of Life Cycle Assessment*, *22*(2), 185-198.

Lokanc, M., Eggert, R., & Redlinger, M. (2015). *The availability of indium: The present, medium term, and long term* (No. NREL/SR-6A20-62409). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Lucas, P., & Wilting, H. (2018). *Using Planetary Boundaries to Support National Implementation of Environment-related: Sustainable Development Goals: Background Report*. PBL Netherlands Environmental Assessment Agency.

Lund, H., & Thellufsen, J. Z. (2019). Advanced Energy Systems Analysis Computer Model Documentation Version 15.

Magagna, D., Hidalgo González, I., Bidoglio, G., & Peteves, S. (2019). WATER ENERGY NEXUS IN EUROPE. European Commission. Joint Research Centre.

Makaire, D., & Ngendakumana, P. (2010). Thermal performance of condensing boilers.

Månberger, A., & Stenqvist, B. (2018). Global metal flows in the renewable energy transition: Exploring the effects of substitutes, technological mix and development. *Energy Policy*, *119*, 226-241.

Masatin, V., Latõšev, E., & Volkova, A. (2016). Evaluation factor for district heating network heat loss with respect to network geometry. *Energy Procedia*, *95*, 279-285.

Mata, É., Ottosson, J., & Nilsson, J. (2020). A review of flexibility of residential electricity demand as climate solution in four EU countries. *Environmental Research Letters*.

Mathiesen, B. V., Lund, R. S., Connolly, D., Ridjan, I., & Nielsen, S. (2015a). Copenhagen Energy Vision: A sustainable vision for bringing a Capital to 100% renewable energy.

Mathiesen, B. V., Hansen, K., Ridjan, I., Lund, H., & Nielsen, S. (2015b). Samsø Energy Vision 2030: Converting Samsø to 100% Renewable Energy.

McDonald, R. I., Fargione, J., Kiesecker, J., Miller, W. M., & Powell, J. (2009). Energy sprawl or energy efficiency: climate policy impacts on natural habitat for the United States of America. *PloS one*, *4*(8), e6802.

McKendry, P. (2002). Energy production from biomass (part 2): conversion technologies. *Bioresource technology*, *83*(1), 47-54.

Meldrum, J., Nettles-Anderson, S., Heath, G., & Macknick, J. (2013). Life cycle water use for electricity generation: a review and harmonization of literature estimates. *Environmental Research Letters*, *8*(1), 015031.

Mernagh, T. P., Bastrakov, E.N., Clarke, J.D.A., de Caritat, P., English, P.M., Howard, F.J.F., Jaireth, S., Magee, J.W., McPherson, A.A., Roach, I.C., Schorder, I.F., Thomas, M. & Wilford, J.R. (2013). *A review of Australian salt lakes and assessment of their potential for strategic resources*. Geoscience Australia.

Meyer, K., Newman, P. (2020). *Planetary Accounting: Quantifying How to Live Within Planetary Limits at Different Scales of Human Activity*. Springer Nature.

Moss, R. L., Tzimas, E., Kara, H., Willis, P., & Kooroshy, J. (2011). Critical metals in strategic energy technologies. *Publications Office of the European Union, Luxembourg*.

Nakada, S., Saygin, D., & Gielen, D. (2014). Global bioenergy supply and demand projections: a working paper for REmap 2030. *International Renewable Energy Agency (IRENA)*, 1-88.

Nationale EnergieAtlas (n.d.). Zonnepotentie velden. Retrieved 11-08-2020, from https://www.nationaleenergieatlas.nl/zonpotentie-velden

Onat, N., & Bayar, H. (2010). The sustainability indicators of power production systems. *Renewable and Sustainable Energy Reviews*, *14*(9), 3108-3115.

Ong, S., Campbell, C., Denholm, P., Margolis, R., & Heath, G. (2013). *Land-use requirements for solar power plants in the United States* (No. NREL/TP-6A20-56290). National Renewable Energy Lab.(NREL), Golden, CO (United States).

Our World In Data, (n.d.). Global Sulphur Dioxide (SO_2) emissions by world region. Retrieved 05-05-2020, from https://ourworldindata.org/grapher/so-emissions-by-world-region-in-million-tonnes

Padinger, R., Aigenbauer, S., & Schmidl, C. (2019). Best practise report on decentralized biomass fired CHP plants and status of biomass fired small-and micro scale CHP technologies.

Pavel, C. C., Lacal-Arántegui, R., Marmier, A., Schüler, D., Tzimas, E., Buchert, M., ... & Blagoeva, D. (2017a). Substitution strategies for reducing the use of rare earths in wind turbines. *Resources Policy*, *52*, 349-357.

Pavel, C. C., Thiel, C., Degreif, S., Blagoeva, D., Buchert, M., Schüler, D., & Tzimas, E. (2017b). Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications. *Sustainable materials and technologies*, *12*, 62-72.

PBL (Planbureau voor de Leefomgeving) (n.d.). Emissies luchtverontreinigende stoffen liggen, op ammoniak na, ruim onder de Europese emissieplafonds voor 2010. Retrieved 18-04-2020, from https://themasites.pbl.nl/balansvandeleefomgeving/jaargang-2018/themas/energie-klimaat-lucht/emissies-luchtverontreinigende-stoffen

Pehl, M., Arvesen, A., Humpenöder, F., Popp, A., Hertwich, E. G., & Luderer, G. (2017). Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nature Energy*, *2*(12), 939-945.

Pfister, S., Saner, D., & Koehler, A. (2011). The environmental relevance of freshwater consumption in global power production. *The International Journal of Life Cycle Assessment*, *16*(6), 580-591.

Pollet, B. G., Staffell, I., & Shang, J. L. (2012). Current status of hybrid, battery and fuel cell electric vehicles: From electrochemistry to market prospects. *Electrochimica Acta*, *84*, 235-249.

Pulles, T., & Appelman, W. (2008). Air pollution from electricity-generating large combustion plants. *EEA Technical Report2008*.

Pure Energy Centre (2012). Launch Of The Greenest Hydrogen Boiler In The World. Retrieved 10-09-2020, from https://pureenergycentre.com/hydrogen-boiler-pure-energy-centre-product-launch/

Pyrhönen, J., Nerg, J., Puranen, J., & Haavisto, M. (2010). Permanent magnet technology in wind power generators. In *The XIX International Conference on Electrical Machines-ICEM 2010* (pp. 1-6). IEEE.

Redlinger, M., Eggert, R., & Woodhouse, M. (2015). Evaluating the availability of gallium, indium, and tellurium from recycled photovoltaic modules. *Solar Energy Materials and Solar Cells*, *138*, 58-71.

Reimer, M. V., Schenk-Mathes, H. Y., Hoffmann, M. F., & Elwert, T. (2018). Recycling Decisions in 2020, 2030, and 2040—When Can Substantial NdFeB Extraction be Expected in the EU?. *Metals*, *8*(11), 867.

Rinne, E., Holttinen, H., Kiviluoma, J., & Rissanen, S. (2018). Effects of turbine technology and land use on wind power resource potential. *Nature Energy*, *3*(6), 494-500.

Ritchie, H. (2017). How much of the world's land would we need in order to feed the global population with the average diet of a given country? *Published online at OurWorldInData.org.* Retrieved 12-05-2020, from https://ourworldindata.org/agricultural-land-by-global-diets#licence

Ritchie, H. and Roser M. (2020). CO_2 and Greenhouse Gas Emissions. *Published online at OurWorldInData.org.* Retrieved 06-05-2020, from https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Rogelj, j.,Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, et al. (2018). Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: *Global Warming of 1.5 °C. An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change.* Intergovernmental Panel on Climate Change.

Roth, S., Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Heck, T., & Schenler, W. (2009). Sustainability of electricity supply technology portfolio. *Annals of Nuclear Energy*, *36*(3), 409-416.

RVO (Rijksdienst Voor Ondernemend Nederland) (2016). Grondgebonden zonneparken Verkenning naar de afwegingskaders rond locatiekeuze en ruimtelijke inpassing in Nederland. https://www.rvo.nl/sites/default/files/2016/09/Grondgebonden%20Zonneparken%20-%20verkenning%20afwegingskadersmetbijlagen.pdf

Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. *Clean Technologies and Environmental Policy*, *16*(2), 329-339.

Santoyo-Castelazo, E., & Azapagic, A. (2014). Sustainability assessment of energy systems: integrating environmental, economic and social aspects. *Journal of Cleaner Production*, *80*, 119-138. And supplementary information document from: https://ars.els-cdn.com/content/image/1-s2.0-S0959652614005381-mmc1.pdf

Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, S. Kadner, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin (2011). Renewable Energy in the Context of Sustainable Development. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Schenler, W., Hirschberg, S., Burgherr, P., Makowski, M., & Granat, J. (2009). Final report on sustainability assessment of advanced electricity supply options.

Schootsma, S. (2017). Benchmark energieverbruik gebouwen. Retrieved 04-06-2020, from https://www.energievastgoed.nl/2017/02/14/benchmark-energieverbruik-gebouwen/#:~:text=ECN%20heeft%20berekend%20dat%20gebouwen,miljoen%20kWh%20(28%20PJ).

Schutter, L. D., & Giljum, S. (2014). A calculation of the EU Bioenergy land footprint-Discussion paper on land use related to EU bioenergy targets for 2020 and an outlook for 2030. *Institute for the Environment and Regional Development, Vienna University of Economics and Business*.

Selman, M., & Greenhalgh, S. (2010). Eutrophication: sources and drivers of nutrient pollution. *Renewable Resources Journal*, *26*(4), 19-26.

Sharifi, A., & Murayama, A. (2015). Viability of using global standards for neighbourhood sustainability assessment: insights from a comparative case study. Journal of Environmental Planning and Management, 58(1), 1-23.

Simon, B., Ziemann, S., & Weil, M. (2015). Potential metal requirement of active materials in lithium-ion battery cells of electric vehicles and its impact on reserves: Focus on Europe. *Resources, Conservation and Recycling*, *104*, 300-310.

Sinha, P., & de Wild-Scholten, M. (2015). Life Cycle Assessment of Silver Replacement With Copper Based Metallization in Tetrasun PV Modules. In *Proceedings of 31st European Photovoltaic Solar Energy Conference and Exhibition* (pp. 2424-2429).

Singh, A., Pant, D., & Olsen, S. I. (Eds.). (2013). *Life cycle assessment of renewable energy sources*. Springer Science & Business Media.

Slade, R., Bauen, A., & Gross, R. (2014). Global bioenergy resources. *Nature Climate Change*, *4*(2), 99-105.

Speirs, J., Contestabile, M., Houari, Y., & Gross, R. (2014). The future of lithium availability for electric vehicle batteries. *Renewable and Sustainable Energy Reviews*, *35*, 183-193.

Squires, J., & Goater, A. (2016). Carbon Footprint of Heat Generation (POST-Parliamentary Office of Science and Technology-UK). *The Parliamentary Office of Science and Technology: London, UK*.

Stamford, L., & Azapagic, A. (2012). Life cycle sustainability assessment of electricity options for the UK. *International Journal of Energy Research*, *36*(14), 1263-1290.

Statista (2020). Number of vehicles in use worldwide 2006-2015. Retrieved 29-08-2020, from https://www.statista.com/statistics/281134/number-of-vehicles-in-use-worldwide/

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., ... & Folke, C. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science*, *347*(6223), 1259855.

Stevens, L., Anderson, B., Cowan, C., Colton, K., & Johnson, D. (2017). The footprint of energy: land use of US electricity production. *STRATA: Logan, UT, USA*. Land use intensity

Stockholm Resilience Centre (n.d.). The nine planetary boundaries. Stockholm University. Retrieved 23-04-2020, from https://www.stockholmresilience.org/research/researchnews/tippingtowardstheunknown/theninepl anetaryboundaries.4.1fe8f33123572b59ab80007039.html

Swain, M., Lovering, J., Blomqvist, L., Nordhaus, T., & Hernandez, R. R. (2015). Land-Use Intensity of Electricity Production: Comparison Across Multiple Sources. *AGUFM*, *2015*, GC51C-1098.

Taveres-Cachat, E., Grynning, S., Thomsen, J., & Selkowitz, S. (2019). Responsive building envelope concepts in zero emission neighborhoods and smart cities-A roadmap to implementation. Building and Environment, 149, 446-457.

Tokimatsu, K., Höök, M., McLellan, B., Wachtmeister, H., Murakami, S., Yasuoka, R., & Nishio, M. (2018). Energy modeling approach to the global energy-mineral nexus: Exploring metal requirements and the well-below 2° C target with 100 percent renewable energy. *Applied Energy*, *225*, 1158-1175.

Tokimatsu, K., Wachtmeister, H., McLellan, B., Davidsson, S., Murakami, S., Höök, M., ... & Nishio, M. (2017). Energy modeling approach to the global energy-mineral nexus: A first look at metal requirements and the 2 C target. *Applied energy*, *207*, 494-509.

United Nations. (2015). Transforming our world: The 2030 agenda for sustainable development. *General Assembley 70 session*.

USGS (U.S. Geological Survey) (2020a). Lithium. Mineral Commodity Summaries. Retrieved 25-05-2020, from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-lithium.pdf

USGS (U.S. Geological Survey) (2020b). Tellurium. Mineral Commodity Summaries. Retrieved 28-05-2020, from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-tellurium.pdf

USGS (U.S. Geological Survey) (2020c). Indium. Mineral Commodity Summaries. Retrieved 28-05-2020, from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-indium.pdf

USGS (U.S. Geological Survey) (2020d). Silver. Mineral Commodity Summaries. Retrieved 22-08-2020, from https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-silver.pdf

USGS (U.S. Geological Survey) (2011). Lithium. Mineral Commodity Summaries. Retrieved 26-05-2020, from https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/lithium/mcs-2011-lithi.pdf

USGS (U.S. Geological Survey) (n.d.). How much silver has been found in the world? Retrieved 23-07-2020, from usgs.gov/faqs/how-much-silver-has-been-found-world?qt-news_science_products=3#qt-news_science_products

Vandecasteele I., Baranzelli C., Perpiña C., Jacobs-Crisioni C., Aurambout J-P., & Lavalle C. (2016). An analysis of water consumption in Europe's energy production sector: The potential impact of the EU Energy Reference Scenario 2013 (LUISA configuration 2014), JRC Technical Report, EUR 28048 EN.

Van der Ploeg, P., Mesman, J. & Hartman, W. (2012). Energietransitie in de Stedendriehoek – Deel I: Technische toets. Een studie naar de effecten van energie- en milieuambities van lokale en regionale overheden en lokale klimaatinitiatieven op het landschap in de Stedendriehoek en mogelijke consequenties voor het energienet. Alliander N.V., Arnhem.

Van Exter, P., Bosch, S., Schipper, B., Sprecher, B., & Kleijn, R. (2018). Metaalvraag van Nederlandse energietransitie. Navigeren in een complexe keten. Metabolic, Copper8, Universiteit Leiden. Retrieved from https://www.copper8.com/wp-content/uploads/2018/12/Metaalvraag-van-de-Nederlandse-Energietransitie.pdf

Van Puijenbroek, P. J. T. M., Cleij, P., & Visser, H. (2010). Nutriënten in het Nederlandse zoete oppervlaktewater: toestand en trends. *PBL Netherlands Environmental Assessment Agency, The Hague, the Netherlands*.

Van Wezel, B., Segers, R., Guis, B., & Geertjes, K. (n.d.). CO_2-emissies uit elektriciteitsopwekking binnen ETS. CBS.

Varma, R. (n.d.). What is the Lithium-Ion Battery Market size? Retrieved 11-08-2020, from https://medium.com/cmfe-market-research-reports/what-is-the-lithium-ion-battery-market-size-95d41b80b0b

Veldman, E., Gibescu, M., Slootweg, H. J., & Kling, W. L. (2013). Scenario-based modelling of future residential electricity demands and assessing their impact on distribution grids. *Energy Policy*, *56*, 233-247.

Walker, S., Labeodan, T., Boxem, G., Maassen, W., & Zeiler, W. (2018). An assessment methodology of sustainable energy transition scenarios for realizing energy neutral neighborhoods. *Applied Energy*, *228*, 2346-2360.

Wang, Y., & Sun, T. (2012). Life cycle assessment of CO2 emissions from wind power plants: Methodology and case studies. *Renewable Energy*, *43*, 30-36.

Watari, T., McLellan, B. C., Ogata, S., & Tezuka, T. (2018). Analysis of potential for critical metal resource constraints in the international energy agency's long-term low-carbon energy scenarios. *Minerals*, *8*(4), 156.

WCED (1987). Our Common Future, World Commission on Environment and Development. Oxford: Oxford University Press.

Werner, T. T., Mudd, G. M., & Jowitt, S. M. (2017). The world's by-product and critical metal resources part III: A global assessment of indium. *Ore Geology Reviews*, *86*, 939-956.

Wiik, M. R. K., Fufa, S. M., Krogstie, J., Ahlers, D., Wyckmans, A., Driscoll, P. A., ... & Gustavsen, A. (2018). Zero Emission Neighbourhoods in Smart Cities: Definition, Key Performance Indicators and Assessment Criteria: Version 1.0. *ZEN Report*.

Wirsenius, S., Azar, C., & Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030?. *Agricultural systems*, *103*(9), 621-638.

Xu, L., Zhang, S., Yang, M., Li, W., & Xu, J. (2018). Environmental effects of China's solar photovoltaic industry during 2011–2016: a life cycle assessment approach. *Journal of Cleaner Production*, *170*, 310-329.

Zhang, C., Wei, Y. L., Cao, P. F., & Lin, M. C. (2018). Energy storage system: Current studies on batteries and power condition system. *Renewable and Sustainable Energy Reviews*, *82*, 3091-3106.

Zhao, Y., Duan, L., Xing, J., Larssen, T., Nielsen, C. P., & Hao, J. (2009). Soil acidification in China: is controlling SO2 emissions enough? *Environ. Sci. Technol.* 2009, 43, 21, 8021-8026

Zijlema, P. J. (2015). The Netherlands: list of fuels and standard CO_2 emission factors. *Version April*.

Appendix A: Explanation of the sustainability indicators that are not considered

In this appendix is explained why the sustainability indicators that are not considered in the research are not relevant in the context of 100% renewable energy systems. Only GHG emissions, land use and the use of critical resources are analysed in the research while 'ozone depletion', 'freshwater use', 'water quality/toxicity', 'terrestrial quality/toxicity' and 'air quality/toxicity' are left out of the research. Below is explained for each of these sustainability indicators why they are excluded of the research.

Water quality and toxicity

Within water quality and toxicity, several specific subcategories can be identified. Although some subcategories are not only affecting the water quality, they are analysed in this section. The subcategories are acidification, eutrophication and water ecotoxicity.

Acidification

The emissions of SO_X, NO_X and NH_3 are nearly exclusively responsible for acidification (Stamford and Azapagic, 2012; Ryberg et al., 2014). These emissions have a regional impact and increases the soil and water acidity that can harm organisms, plants and buildings. The emissions of SO_X and NO_X are mainly caused by the production of electricity due to fossil fuels (like coal, oil and gas) and NH_3 emissions are primarily caused by chemical and fertilizer manufacturing companies (Zhao et al., 2009; Ryberg et al., 2014; Dahiya and Myllyvirta, 2019). The main cause of NO_X emissions is transport (European Commission, 2017). So NH_3 emission occurs outside the energy sector and the main source of SO_X and NO_X are fossil fuels.

SO_X is emitted in the form of SO_2 with fossil fuel combustion (Pulles and Appelman, 2008) and the global SO_2 emissions have decreased from 151.5 Mt in 1980 to 87 Mt in 2010 (Our World In Data, n.d.). In Europe and North America, the SO_2 emissions has even decreased with 70-80% since 1990 and in the Netherlands the SO_2 emissions reduced from 195 to 31 Gg between 1990 and 2012 which is already below the National Emission Ceiling (NEC) for 2030 (Aas et al., 2019; CLO, 2018; European Commission, 2019). This NEC target of the European Commission is set with the aim to reduce the acidification and improve air quality (European Commission, 2016). According to different sources, the global NO_X emissions in 2014 were 55.6 Mt N/year (Geddes and Martin, 2017), 50 Mt N/year (Gieseke et al., 2019) and around 140 Mt NO_2/year (Hoesly et al., 2018). In the Netherlands these emissions have decreased from 580 Gg NO_X in 1990 to around 250 Gg NO_X in 2012 and are well below the NEC target (EEA, 2014). These emissions are predominantly caused combustion of fossil fuels for transport and electricity and heat production (EEA, 2014).

Because NO_X and SO_2 emission are generally caused by fossil fuels and the starting point of this study is a 100% renewable energy system, the acidification potential, SO_2 and NO_X emission are not considered as relevant in this study because renewable energy systems will not contribute significantly to acidification and the acidification potential will only become lower than nowadays due to renewable energy system (Kouloumpis et al., 2015). Besides the neglectable contribution of renewable energy supply to acidification, the planetary boundary of acidification is not exceeded yet while the global SO_2 emissions are decreasing over the past decades even though the energy supply was largely provided by fossil sources (Steffen et al., 2015; Our World In Data, n.d.; Aas et al., 2019). The NO_X emission are also decreasing and renewable energy systems will barely contribute to NO_X emission. Therefore the acidification will not be taken into account in this study.

Eutrophication

Eutrophication is caused by anthropogenic nutrient inputs to aquatic ecosystems that can result in harmful ‘algae blooms’ and ‘dead zones’ in coastal marine ecosystems (Conley et al., 2009). Also elements within energy supply systems contribute to eutrophication, currently mainly due to emissions of phosphate from lignite and hard coal mining with the purpose of electricity generation (Atilgan and Azapagic, 2016a). Besides fossil sources like lignite, energy production from renewable sources contribute to eutrophication as well but to a much smaller extent than fossil fuels (Hydro-Québec, 2014; Stamford and Azapagic, 2012). These mainly arise from the construction stage by emission of phosphates to freshwater related to copper and steel production, but also other emissions are involved like NO_X emissions to air (Atilgan and Azapagic, 2016b). The primary sources of eutrophication are sewage treatment plants, industry, septic systems, urban stormwater runoff, agricultural fertilizers, livestock operation, aquaculture and fossil fuel combustion (Selman and Greenhalgh, 2010). When fossil fuels are excluded from energy systems, they will have a minor contribution to eutrophication, except for bioenergy as agricultural fertilizers are in involved in biomass production.

Looking at the nitrogen and phosphorus emission to surface water, it can be seen that it originates almost exclusively from sewage treatment plants and runoff from agricultural land (van Puijenbroek et al., 2010). In combination with the fact the exclusion of fossil sources take away nearly all energy related eutrophication emissions, this eutrophication indicator is not considered as relevant anymore in the context of renewable energy systems as the contribution of energy supply is neglectable if only renewable sources are incorporated.

Ecotoxicity

Freshwater ecotoxicity is used as an indicator to represent a range of toxicity indicators like marine aquatic- and terrestrial ecotoxicity. This is also done in other studies because the other types of ecotoxicity are caused by the same pollutants and they are indicated by the same indicator (Hertwich et al., 2015; Gibon et al., 2017). Within a decarbonized renewable energy system, the freshwater ecotoxicity potential will decrease inherently, only for geothermal energy the ecotoxicity is higher than the current mix (Gibon et al., 2017; Kouloumpis et al., 2015; Hertwich et al., 2015). As the ecotoxicity will decrease with a decrease in carbon emissions due to the exclusion of fossil sources, the ecotoxicity indicators are not considered as relevant in the sustainability assessment of renewable energy systems. It is assumed that the impact will be reduced and stay within sustainable boundaries when the sustainability targets for global warming, land use and resources/materials are met.

Air quality and toxicity

For air quality and toxicity, only the subcategory of Particulate Matter (PM) emissions and photochemical smog are considered because other pollutant like GHG, NO_X, SO_X and ecotoxicity potential is already discussed in other categories.

Particulate Matter

Emissions of particulate matter (PM) related to energy system mainly occur from the combustion of fossil fuels or biomass and can cause severe human health issues (Ghafghazi et al., 2011). The NEC targets of the EU for each country are defined with the intention to improve the air quality and to come closer to reach the long term target of air quality levels that do not have significant adverse effects for humanity and nature (PBL, n.d.). From 1998, the PM10 concentration has not exceeded the maximum EU value of 40 $\mu g/m^3$ at any measuring location in the Netherlands and is left out of the NEC targets (European Commission, 2019). The PM10 emissions are already at a safe level and the current contribution of energy systems is due to combustion of fossil fuels, what does not happen in renewable energy systems. Therefore, PM10 emissions are not considered as a problem with significant contribution of renewable energy sources and is therefore left out of the study.

Within the Netherlands, the total PM2.5 emissions have decreased from 46 Gg in 1990 to 13 Gg in 2012 and the ‘energy use and supply’ sector is responsible for 25% of the PM2.5 emission (EEA, 2014). Since the emissions are already decreasing significantly, fossil fuels are by far the major energy related contributor, and the emission of PM will decrease with the shift from fossil fuels to renewable alternatives, the impact of renewable energy systems by PM emissions is so small that it is not be considered in this study.

Photochemical smog

The indicator for photochemical smog creation is the photochemical ozone creation potential (POCP) that is caused primarily by Volatile Organic Compounds (VOCs) and NO_X emissions (Stamford and Azapagic, 2012). In the presence of light, ozone can formed what is an harmful pollutant at ground level and is a major component of urban air smog (Evuti, 2013). As explained before, the impact of energy related NO_X emission will be diminished to acceptable levels when solely renewable energy supply is incorporated. For global VOC emissions, a decreasing trend can be seen over the past years and the share of the energy production and consumption sector is 11.2% (Evuti, 2013; EEA, 2014). Again these energy related emission are primarily caused by fossil fuels. Renewable alternatives have POCP levels per kWh energy production that are more than 10 times lower than fossil fuels (Hydro-Québec, 2014). As well as for previous mentioned indicators, photochemical ozone formation will decrease in renewable low carbon systems, relative to the current situation (Gibon et al., 2015).

Ozone depletion

In contrast to ground-level ozone that is a harmful air pollutant, stratospheric ozone prevents the earth for too many UV rays reaching the earth’s surface. This is a problem with global impact and is mainly caused by the emission of halocarbons chlorofluorocarbons (CFCs) (Stamford and Azapagic, 2012; Hydro-Québec, 2014). Ozone depletion is quantified by calculating its ozone depleting potential (ODP) (Stamford and Azapagic, 2012). The largest energy supply related source of ozone depletion is caused by extraction, production and transportation of nuclear, oil and natural gas. For coal, solar PV, CSP, biomass and biogas, the impact is only one tenth of the previous mentioned sources and are caused by equipment manufacturing (for solar power) and combustion (biomass and coal). Looking at ODP, wind and hydropower score even better than solar Coal, PV, CSP and bioenergy (Hydro-Québec, 2014). In contrary to the previous mentioned indicators, this indicator will not decrease in impact if the energy system become low carbon and renewable as the ODP of coal is lower than the ODP of CSP, solar PV, biogas and nuclear (Hydro-Québec, 2014). Nevertheless the contribution of energy supply is small as the main sources of ozone layer depletion are manufactured chemicals in a variety of applications like refrigeration, air conditioning and foal blowing (Hegglin et al., 2015).

The minimum stratospheric ozone concentration is set at 200 DU (89.2 mmol/m²) by the planetary boundary framework (Steffen et al., 2015). The annual minimum measured ozone concentration (around 200 DU) is stable since 2000 and is expected to rise over the coming decades because ozone-depleting substances have been phased out (Steffen et al., 2015). In 1988 the global ozone-depleting substance emissions were 1.46 Mt CFC11-eq and in 2014 only 0.32 Mt CFC11-eq (Hegglin et al., 2015). The stratospheric ozone concentration is currently on safe values a safely within the planetary boundary for ozone depletion (Steffen et al., 2015). This in combination with the expected rise in stratospheric ozone concentration, the steadily decreasing emissions of ozone-depleting substances, and the relatively small contribution of energy systems to ozone depletion, makes that this it is assumed that renewable energy systems have neglectable impact to ozone depletion while it is already within sustainable boundaries. Therefore, it is not taken into account in this study.

Freshwater use

Producing energy requires significant amounts of freshwater as water is used in nearly all processes in the energy sector including resource extraction (fossil, nuclear and biomass) and energy generation (Spang et al., 2014). Quantification of water consumption during energy generation is difficult, especially for renewable energy technologies (Evans et al. 2009). It can be hard to distinguish between water withdrawal (when water is taken and returned to circulation) and water consumption (when water is removed from circulation). Water consumption seems to be a better indicator as the water that is 'lost' will cause the impact (Evans et al., 2009). Energy production has a considerable share in total water consumption and could cause damage to human health and ecosystems (Pfister et al., 2011). In the 'new policies scenario' in the world energy outlook of the IEA, Europe is the only region with decreased water consumption for energy production (IEA, 2012).

In general, renewable energy (especially wind and solar) has a lower water consumption than fossil fuels except for bioenergy (see table below). This indicate that a shift towards a renewable energy supply will not increase the water consumption. The planetary boundary of freshwater consumption is defined as a global maximum amount of consumptive blue water use of 4000 km^3/yr (uncertainty zone 4000-6000) while the current global water consumption is around 2600 km^3/yr (Steffen et al., 2015). So as the current water consumption is safely below the planetary boundary, and renewable energy systems will not contribute more to water consumption that the current energy supply, this indicator is considered already as sustainable.

Table 17 - Freshwater consumption for energy generation sources.

	Freshwater consumption (median) (kg/kWh)
Coal	1.70 [1, 2, 3, 4, 5, 6, 7]
Natural gas	1.25 [1, 2, 3, 4, 6, 7, 8]
Oil	0.90 [8]
Nuclear	2.19 [2, 3, 4, 5, 6, 8]
Hydroelectric	21.44 [1, 4, 5, 6, 7]
Hydrogen fuel cell	2.0 [6]
Solar PV	0.38 [2, 3, 4, 5, 6, 7, 8]
CSP	3.29 [3, 5]
Geothermal	0.85 [1, 3, 5, 6, 8]
Wind	0.0022 [2, 3, 4, 5, 6, 7, 8]
Biomass waste	3.2 [1]
Biomass energy crops	34 [1]

Data sources: 1: Larson et al. (2007); 2: Vandecasteele et al. (2016); 3: Meldrum et al. (2013); 4: Evans et al. (2010); 5: Jacobsen (2009); 6: Onat and Bayer (2010); 7: Evans et al. (2009); 8: Magagna et al. (2019).

Appendix B: Calculations of energy demand in Haven-Stad

In this appendix is explained how the two types of energy demand for Haven-Stad are calculated and on the basis of which data sources this is done. At first the required characteristics of the neighbourhood are explained after which the actual demand is calculated on the basis of current energy demand in Haven-Stad and on the basis of low energy demand with a share of flexible electricity demand.

Characteristics of Haven-Stad

In the table below, the characteristics of the future Haven-Stad neighbourhood are shown. The data is gained from a development strategy document of the municipality of Amsterdam in which they express their plans for the transition of the neighbourhood in development (Gemeente Amsterdam, 2017). The neighbourhood is divided in 12 sub-areas for which the amount of houses and workplaces are shown below.

Table 18 - building area, houses and workplace in Haven-Stad for each sub-area (Gemeente Amsterdam, 2017).

	Houses	Workplaces
Alfadriehoek	5200	3467
Coen- en Vlothaven	15400	10267
Cornelis Douwes 0-1	6900	4600
Cornelis Douwes 2-3	9600	6400
Groot Westerpark	Park	
Melkweg Oostzanerwerf	1600	266
Minervahaven	11620	7747
Noorder ij-plas	Park	
Sloterdijk Centrum	7410	15515
Sloterdijk 1	11220	7480
Sportpark transformatorweg en Amsterbakken	1880	1253
Zaanstraat Emplacement	1820	1213
Totaal	**72650**	**58208**

The average number of residents per household is Haven-Stad is expected to be 1.75 (Gemeente Amsterdam, 2017). With an expected number of houses of 72650 (table 18), the future number of residents of Haven-Stad is assumed to be 127138. In urban areas like Amsterdam, the number of cars per household is relatively low in comparison to households in rural areas. In Amsterdam, the amount of cars per household is 0.4 (CBS, 2016a). In combination with the numbers of households mentioned in the table above, the expected amount of cars in Haven-Stad is around 29000. As the average distance per car per year in the Netherlands in 13000 km, the total travelled kilometres by cars of inhabitants of Haven-Stad is around 378 million kilometres per year (CBS, 2019b).

Energy demand Haven-Stad (Based on current average energy demand)

The energy demand is assumed to be equal in all designs. The energy demand consists of the electricity- and heat demand of households and utility buildings, as well as the energy demand for electric vehicles. This section shows calculation and overview of the energy demand in Haven-Stad on the basis of the current average energy demand in Amsterdam.

Households

In Amsterdam, the electricity demand per household is 2090 kWh/year (7.5 GJ/year) and the natural gas demand is 870 m³ (CBS, 2020c). With the conversion factor of 31.65 MJ/m³ natural gas (van der Ploeg et al., 2012), and the assumption that natural gas demand equals the heat demand, the heat demand per household in Amsterdam is 27.5 GJ/household/year. With 72650 household in Haven-Stad (table 18), the heat demand for households in Haven-Stad is 2.0 PJ/year. With an annual electricity demand for households of 0.55 PJ/year, the total energy demand for households is 2.55 PJ/year.

Utility buildings

In the development strategy document, the municipality of Amsterdam stated that the gross floor area per workplace is 30m² on average for Haven-Stad (Gemeente Amsterdam, 2017). As shown in table 18, the expected number of workplaces is 58208 so the gross floor area for workplaces is 1746240 m². It is assumed that all workplaces are located in office building, therefore the gas- and electricity demand intensity of office buildings are used. The natural gas use intensity is 17 m³/m²/yr (assumed to be equal to heat demand) and the electricity use intensity of office buildings is 60 kWh/m²/yr (CBS, 2016b; Schootsma, 2017). Using these numbers and the conversion factor of 31.65 MJ/m³ natural gas (van de Ploeg et al., 2012), the annual heat and electricity demand of utility buildings in Haven-Stad are expected to be respectively 940 TJ and 377 TJ. The total energy demand on the basis of the current average energy demand is shown in as overview in the table below.

Table 19 - Expected energy demand for households and utility buildings in Haven-Stad, based on current average energy demand in Amsterdam.

	Heat demand (PJ/yr)	Electricity demand (PJ/yr)	**Total (PJ/yr)**
Households	2.0	0.55	**2.55**
Utility buildings	0.94	0.38	**1.32**
Total	**2.94**	**0.93**	**3.87**

Energy demand Haven-Stad (based on low and flexible energy demand)

In the table above, the energy demand for Haven-Stad is shown, based on the assumption that the average heat and electricity demand per household/utility building is equal to the current average energy demand for those building in Amsterdam. As all building in Haven-Stad are yet to be built, and new constructed building are generally better isolated, it could be possible that the overall energy demand will be lower than the current energy demand. In the development strategy document of the municipality of Amsterdam is stated that the average usage surface per household is 60 m² (Gemeente Amsterdam, 2017). For houses with a surface area between 50 and 75 m² that are built in 2015 or later, the gas demand for heating is 759 m³/yr (CBS, 2018b). Using the conversion factor of 31.65 MJ/m³ for natural gas (van de Ploeg et al., 2012), the heat demand for households in Haven-Stad is 1.75 PJ/yr. That is 12.8% less that the current average energy demand. If new built utility buildings have a heat demand that is 12.8% less than the current average, the heat demand for utility buildings in Haven-Stad is 0.82 PJ/yr. For electricity, a share of flexible demand is assumed as this is often seen as required to achieve climate goals (Mata et al., 2020). It helps to manage intermittent energy sources and can be provided by smart flexibility measures like price mechanisms, user-centred control strategies, automated shifting appliances, EV charging algorithms and consumer feedback (Mata et al. 2020). In west European countries, between 2% and 18% of the residential electricity demand can be shifted (Mata et al., 2020). For this study the average is assumed, so 10% of the electricity demand could be shifted. The energy demand based on the energy use of newly constructed buildings with partly flexible demand is shown in the table below.

Table 20 - Expected energy demand for households and utility buildings in Haven-Stad, based on energy consumption of newly constructed buildings

	Heat demand (PJ/yr)	Electricity demand (PJ/yr)	**Total (PJ/yr)**
Households	1.75	0.55	**2.3**
Utility buildings	0.82	0.38	**1.2**
Total	**2.57**	**0.93**	**3.5**
Of which flexible	-	0.093	-

Appendix C: Input and output data of EnergyPLAN

To compose the designs and simulate them in EnergyPLAN, a set of input data is required concerning the different components of the energy system designs. In this appendix, the input data that is used in EnergyPLAN is shown and explained. At first the input values are shown in the table below that are similar for each design regarding the efficiency and hourly distributions of the different energy sources and production technologies. The used values of efficiency and COP are not exactly mentioned in the data sources by the data sources show that the used values are in a realistic range. This is done for transparency and for the reproducibility of the research.

Table 21 - Values that are generally used in EnergyPLAN, not specific for one design.

Variable	Used value	Data source
Charge and discharge efficiency Li-ion battery	95%	beaudin et al., 2014
Efficiency biomass boiler	85%	Hebenstreit et al., 2011
Efficiency biomass PP	30%	Padinger et al., 2019
Electric efficiency biomass CHP	25%	Padinger et al., 2019
Thermal efficiency biomass CHP	70%	Padinger et al., 2019
COP heat pumps	3.5	Fischer and Madani (2017
Thermal efficiency natural gas boiler	90%	Makaire and Ngendakumana, 2010
District heating network losses	10%	Masatin et al., 2016
Efficiency electrolyser hydrogen production	80%	Kumar and Himabindu, 2019
El. Efficiency Hydrogen PP (fuel cells)	50%	Dodds et al., 2015
Hydrogen boiler	90%	Pure Energy Centre, 2012
Amount of cars	29000	See appendix B
Kilometres per year by car	378 million km/year	See appendix B
Lifecycle GHG emissions gasoline	94.6 kg CO_2-eq./GJ	EPA, n.d.
Lifecycle GHG emissions diesel	91.9 kg CO_2-eq./GJ	EPA, n.d.

For electricity demand, a hourly distribution is used from a measurement by Alliander for a region that is comparable to Haven-Stad. As EnergyPLAN normalises the values, the exact values are not relevant, only the differences between the hours in the year. For wind and solar PV, hourly generation profiles are used that are gained from Alliander as well. As there was no specific distribution for offshore wind, the distribution of onshore is used with a correction factor to manage the higher capacity factor of offshore wind turbines. The hourly distribution causes a capacity factor for onshore wind of 0.28 and the correction factor has changed the capacity factor for offshore wind to 0.38 as that is a realistic difference between onshore and offshore wind turbines (Boccard, 2009). The hourly distribution for solar PV is also used for solar thermal as the profile of solar irradiance for PV and solar thermal are similar. For the hourly distribution for heat demand, a distribution is used that is included in the EnergyPLAN model. For geothermal heat, a constant production is commonly used, but as the heat demand in the summer is much lower than in the winter, a constant production is assumed for the winter while zero production is assumed in the summer.

Also choices need to be made regarding the simulation strategy. In all designs is chosen for an technical simulation rather than the market economic simulation. For the technical simulation strategy, option 2 is chosen: Balancing both heat and electricity demand. The last choice that needed to be was for the individual heat pump simulation. For that, option 1 is chosen: individual heat pumps and electric boilers seek to utilise only critical excel production.

Using the above mentioned input values, the energy demand values calculated in appendix B and the capacities for the energy production and storage technologies that are shown in section 3.8.1, the designs are simulated in EnergyPLAN. In figure 23 to 28, the complete output documents of the designs are shown. In table 23, the primary energy use is shown. For biomass, the primary energy is shown before the final conversion step, and for the remaining energy sources, the primary energy represent the actual energy production. Also the potential energy that could have been produced is shown, because for wind and solar PV, not all potential energy is used as the demand and storage capacity was not always sufficient to consume the produced electricity at peak moments. These potential energy production are based on the installed capacity and hourly distribution and are provided by EnergyPLAN. They are used to calculate the environmental impacts of GHG emissions and land use that are shown in the thesis by multiplying the potential energy production by the carbon/land use intensity. This is because the installed capacity determine the land use and lifecycle GHG emissions, rather than the actual energy production. As the carbon- and land use intensity are given per MWh of energy production, the potential amount of MWh energy production per year is calculated for the installed capacity and shown in table 23. For fossil fuels and biomass, the primary energy use determine the impact so for biomass and fossil fuels these values are used for the impact calculation. Therefore no values are shown for them in the table below as the potential energy with the installed capacity for fossil fuels and biomass are not relevant in this thesis.

An excess of electricity production in an energy system is not desirable. Therefore EnergyPLAN provide multiple options to regulate Critical Excess Electricity Production (CEEP). There are seven options that could be considered for the designs and an it is possible to specify one or more numbers that are than treated in the specified order. The options are (Lund and Thellufsen, 2019):
1: Reducing RES1 and RES2
2: Reducing CHP production in group 2 (Replacing with boiler)
3: Reducing CHP production in group 3 (Replacing with boiler)
4: Replacing boiler production with electric heating in group 2.
5: Replacing boiler production with electric heating in group 3.
6: Reducing RES4 and RES5
7: Reducing power plant production in combination with RES1, RES2, RES3 and RES4

In the table below, the order that is chosen in the different designs is shown.

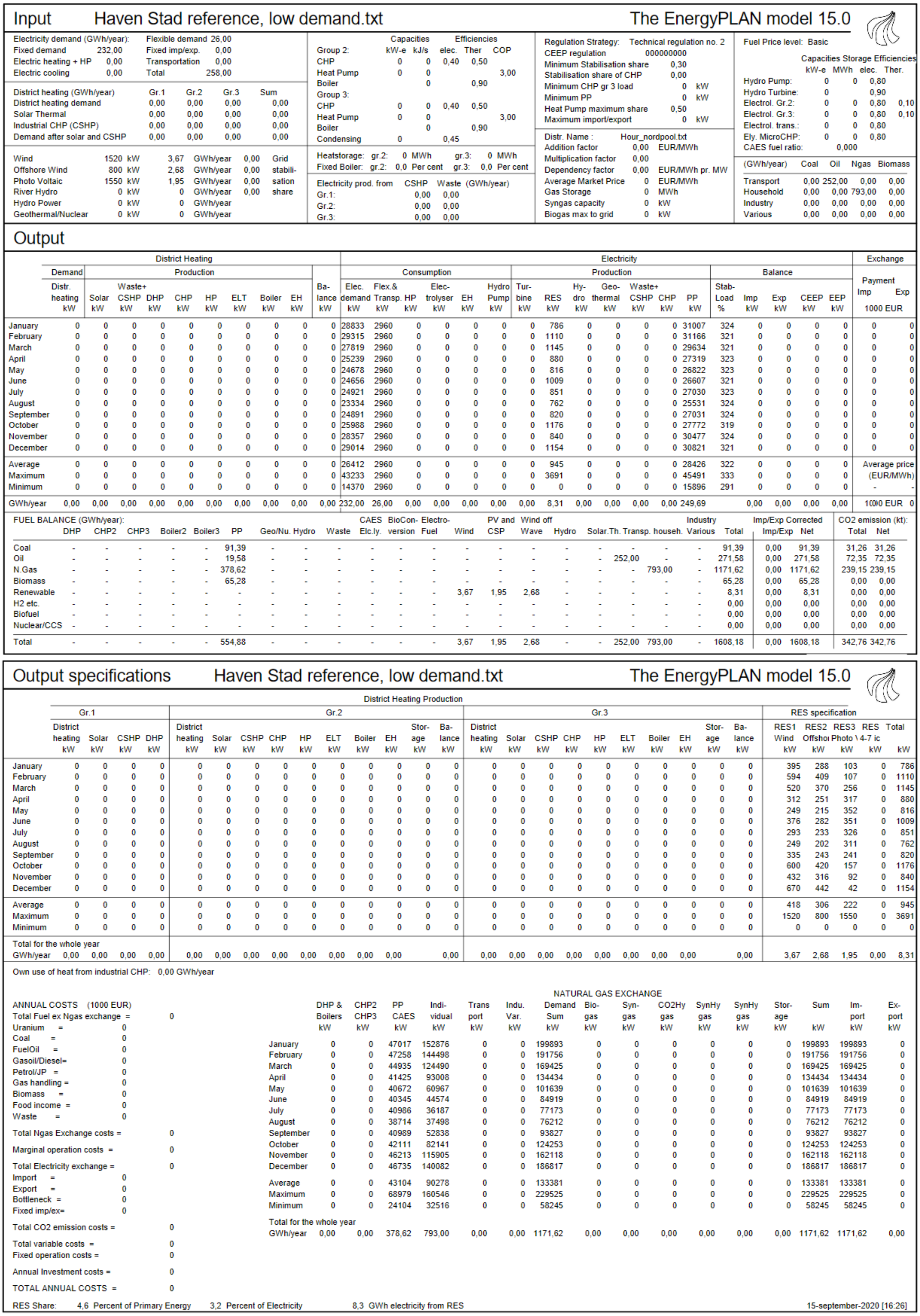
Table 22 - The order of CEEP regulation measures used in EnergyPLAN for the different designs.

	Order of CEEP regulation measures
Reference	-
All-electric	2-3-4-5-7
Minimum land use	5-7
Low critical resource	3-5-7
Central	2-3-4-5-7
Biomass	7

Table 23 - primary energy use in the designs by energy source in TWh/yr. Also the potential primary energy production with the installed capacity. For the two types of energy demand.

	Primary energy, Current average energy demand		Primary energy, Low/flexible energy demand	
	Primary energy	Potential with installed capacity	Primary energy	Potential with installed capacity
	Reference design			
Coal	0.091		0.091	
Oil	0.272		0.272	
Natural gas	1.286		1.172	
Biomass	0.065		0.065	
Onshore wind	0.0037	0.0037	0.0037	0.0037
Offshore wind	0.0027	0.0027	0.0027	0.0027
Solar PV	0.0020	0.0020	0.0020	0.0020
	All-electric design			
Biomass	0.11		0.10	
Onshore wind	0.09	0.19	0.08	0.17
Offshore wind	0.32	0.40	0.31	0.40
Solar PV	0.14	0.15	0.13	0.14
	Minimum land use design			
Onshore wind	0.06	0.15	0.08	0.12
Offshore wind	0.47	0.59	0.39	0.42
Solar PV	0.12	0.13	0.11	0.11
Solar thermal	0.22	0.22	0.22	0.22
Geothermal	0.35	0.35	0.30	0.30
	Low critical resources design			
Biomass	0.70		0.66	
Offshore wind	0.16	0.17	0.16	0.16
Solar PV	0.05	0.05	0.05	0.05
Solar thermal	0.10	0.10	0.10	0.10
Geothermal	0.15	0.15	0.15	0.15
	Central design			
Biomass	0.41		0.39	
Onshore wind	0.11	0.19	0.11	0.17
Offshore wind	0.46	0.49	0.43	0.45
Solar PV	0.06	0.06	0.06	0.06
Solar thermal	0.09	0.09	0.09	0.09
	Biomass design			
Biomass	0.83		0.77	
Onshore wind	0.14	0.16	0.14	0.15
Solar PV	0.08	0.08	0.07	0.08
Solar thermal	0.14	0.14	0.14	0.14

Below, in figure 23 to 28, the output documents of the designs are shown for each design with the low/flexible energy demand. For the current average energy demand, the output documents look slightly different due to the different input values that can be seen in table 4.



```
Input        Haven Stad reference, low demand.txt                                   The EnergyPLAN model 15.0

Electricity demand (GWh/year):  Flexible demand 26,00   |                  Capacities      Efficiencies   | Regulation Strategy:   Technical regulation no. 2 | Fuel Price level:  Basic
Fixed demand          232,00    Fixed imp/exp.     0,00 | Group 2:         kW-e  kJ/s   elec.  Ther  COP  | CEEP regulation              000000000            |
Electric heating + HP   0,00    Transportation     0,00 | CHP                 0     0   0,40   0,50       | Minimum Stabilisation share       0,30            |         Capacities Storage Efficiencies
Electric cooling        0,00    Total            258,00 | Heat Pump           0     0                3,00 | Stabilisation share of CHP        0,00            |          kW-e   MWh   elec.  Ther.
                                                        | Boiler                    0          0,90       | Minimum CHP gr 3 load                0  kW        | Hydro Pump:         0      0   0,80
District heating (GWh/year)   Gr.1    Gr.2    Gr.3    Sum | Group 3:                                      | Minimum PP                           0  kW        | Hydro Turbine:      0          0,90
District heating demand       0,00    0,00    0,00    0,00 | CHP                 0     0   0,40   0,50     | Heat Pump maximum share           0,50            | Electrol. Gr.2:     0      0   0,80   0,10
Solar Thermal                 0,00    0,00    0,00    0,00 | Heat Pump           0     0                3,00 | Maximum import/export             0  kW         | Electrol. Gr.3:     0      0   0,80   0,10
Industrial CHP (CSHP)         0,00    0,00    0,00    0,00 | Boiler                    0          0,90     |                                                   | Electrol. trans.:   0      0   0,80
Demand after solar and CSHP   0,00    0,00    0,00    0,00 | Condensing          0         0,45            | Distr. Name :          Hour_nordpool.txt          | Ely. MicroCHP:      0      0   0,80
                                                        |                                                 | Addition factor         0,00   EUR/MWh            | CAES fuel ratio:         0,000
Wind                 1520  kW     3,67  GWh/year  0,00  Grid     | Heatstorage:  gr.2:    0  MWh     gr.3:    0  MWh   | Multiplication factor   0,00                      |
Offshore Wind         800  kW     2,68  GWh/year  0,00  stabili- | Fixed Boiler:  gr.2:  0,0  Per cent  gr.3:  0,0  Per cent | Dependency factor  0,00  EUR/MWh pr. MW | (GWh/year)   Coal     Oil    Ngas  Biomass
Photo Voltaic        1550  kW     1,95  GWh/year  0,00  sation   |                                                   | Average Market Price       0   EUR/MWh           | Transport    0,00  252,00    0,00    0,00
River Hydro             0  kW        0  GWh/year  0,00  share    | Electricity prod. from   CSHP   Waste  (GWh/year) | Gas Storage                0   MWh               | Household    0,00    0,00  793,00    0,00
Hydro Power             0  kW        0  GWh/year                 | Gr.1:                    0,00    0,00             | Syngas capacity            0   kW                | Industry     0,00    0,00    0,00    0,00
Geothermal/Nuclear      0  kW        0  GWh/year                 | Gr.2:                    0,00    0,00             | Biogas max to grid         0   kW                | Various      0,00    0,00    0,00    0,00
                                                                 | Gr.3:                    0,00    0,00             |
```

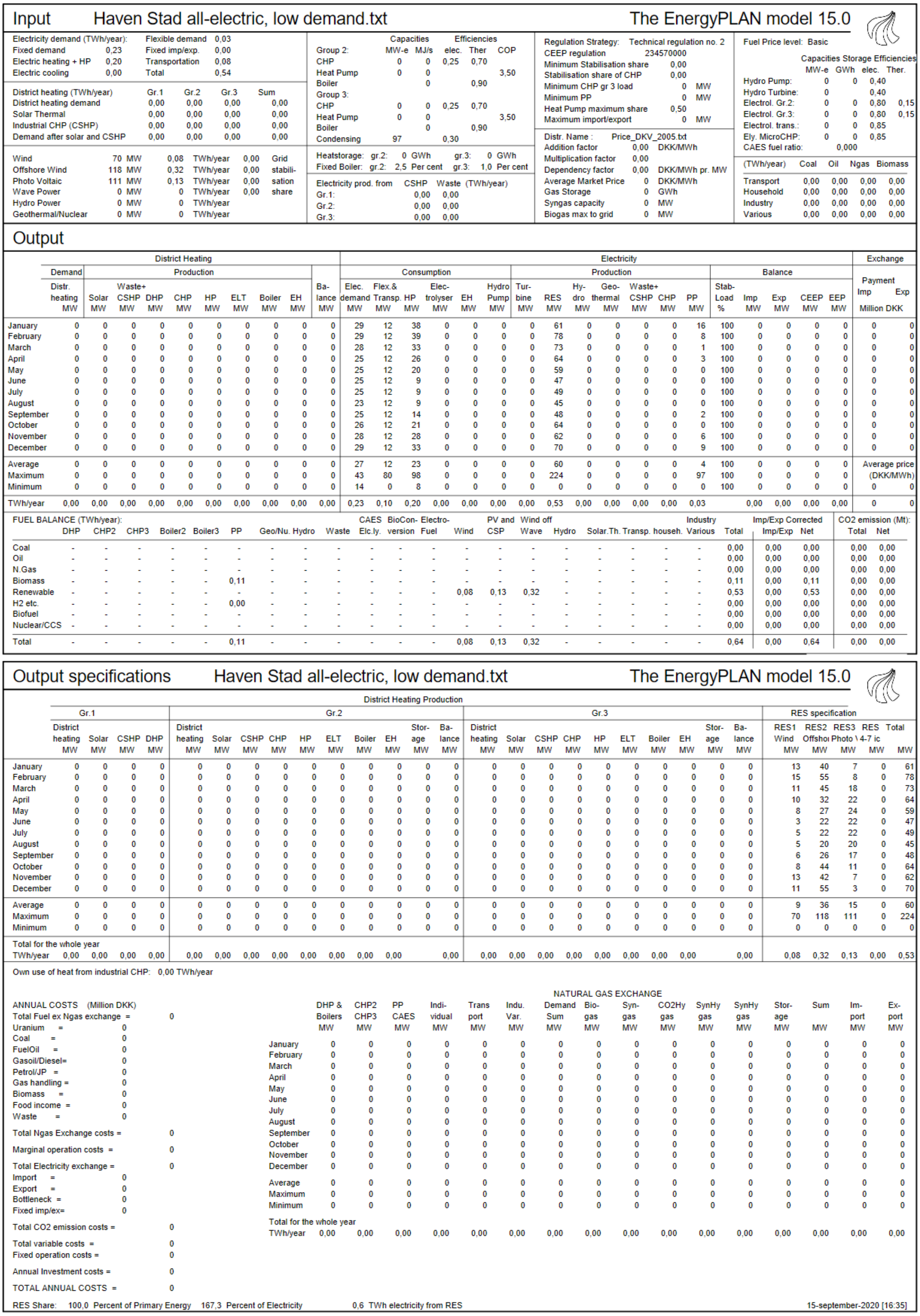
```
Output

                         District Heating                          |                                              Electricity                                                          | Exchange
           Demand  |                   Production               |      |                 Consumption                 |                    Production                    |          Balance            |
           Distr.        Waste+                                    Ba-  | Elec.  Flex.&        Elec-         Hydro | Tur-         Hy-   Geo-   Waste+                | Stab-                            | Payment
           heating Solar CSHP DHP  CHP   HP   ELT  Boiler  EH     lance | demand Transp. HP   trolyser  EH   Pump  | bine   RES   dro  thermal  CSHP  CHP    PP   | Load   Imp   Exp   CEEP  EEP  | Imp     Exp
           kW      kW    kW   kW   kW    kW   kW   kW      kW     kW    | kW     kW      kW   kW        kW   kW    | kW     kW    kW   kW       kW    kW     kW   | %      kW    kW    kW    kW   | 1000 EUR

January    0       0     0    0    0     0    0    0       0      0     | 28833  2960    0    0         0    0     | 0      786   0    0        0     0   31007  | 324    0     0     0     0    | 0       0
February   0       0     0    0    0     0    0    0       0      0     | 29315  2960    0    0         0    0     | 0      1110  0    0        0     0   31166  | 321    0     0     0     0    | 0       0
March      0       0     0    0    0     0    0    0       0      0     | 27819  2960    0    0         0    0     | 0      1145  0    0        0     0   29634  | 321    0     0     0     0    | 0       0
April      0       0     0    0    0     0    0    0       0      0     | 25239  2960    0    0         0    0     | 0      880   0    0        0     0   27319  | 323    0     0     0     0    | 0       0
May        0       0     0    0    0     0    0    0       0      0     | 24678  2960    0    0         0    0     | 0      816   0    0        0     0   26822  | 323    0     0     0     0    | 0       0
June       0       0     0    0    0     0    0    0       0      0     | 24656  2960    0    0         0    0     | 0      1009  0    0        0     0   26607  | 321    0     0     0     0    | 0       0
July       0       0     0    0    0     0    0    0       0      0     | 24921  2960    0    0         0    0     | 0      851   0    0        0     0   27030  | 323    0     0     0     0    | 0       0
August     0       0     0    0    0     0    0    0       0      0     | 23334  2960    0    0         0    0     | 0      762   0    0        0     0   25531  | 324    0     0     0     0    | 0       0
September  0       0     0    0    0     0    0    0       0      0     | 24891  2960    0    0         0    0     | 0      820   0    0        0     0   27031  | 324    0     0     0     0    | 0       0
October    0       0     0    0    0     0    0    0       0      0     | 25988  2960    0    0         0    0     | 0      1176  0    0        0     0   27772  | 319    0     0     0     0    | 0       0
November   0       0     0    0    0     0    0    0       0      0     | 28357  2960    0    0         0    0     | 0      840   0    0        0     0   30477  | 324    0     0     0     0    | 0       0
December   0       0     0    0    0     0    0    0       0      0     | 29014  2960    0    0         0    0     | 0      1154  0    0        0     0   30821  | 321    0     0     0     0    | 0       0

Average    0       0     0    0    0     0    0    0       0      0     | 26412  2960    0    0         0    0     | 0      945   0    0        0     0   28426  | 322    0     0     0     0    | Average price
Maximum    0       0     0    0    0     0    0    0       0      0     | 43233  2960    0    0         0    0     | 0      3691  0    0        0     0   45491  | 333    0     0     0     0    | (EUR/MWh)
Minimum    0       0     0    0    0     0    0    0       0      0     | 14370  2960    0    0         0    0     | 0      0     0    0        0     0   15896  | 291    0     0     0     0    | -       -

GWh/year   0,00    0,00  0,00 0,00 0,00  0,00 0,00 0,00    0,00   0,00  | 232,00 26,00   0,00 0,00      0,00 0,00  | 0,00   8,31  0,00 0,00     0,00  0,00 249,69 |        0,00  0,00  0,00  0,00 | 1000 EUR  0
```

```
FUEL BALANCE (GWh/year):                                             CAES  BioCon- Electro-        PV and Wind off                                  Industry        | Imp/Exp Corrected | CO2 emission (kt):
            DHP  CHP2  CHP3  Boiler2  Boiler3  PP      Geo/Nu. Hydro  Waste  Elc.ly. version Fuel   Wind  CSP    Wave   Hydro  Solar.Th. Transp. househ. Various  Total   | Imp/Exp  Net      | Total   Net

Coal        -    -     -     -        -        91,39   -       -      -      -      -       -      -     -      -      -      -         -       -       -        91,39   | 0,00     91,39    | 31,26   31,26
Oil         -    -     -     -        -        19,58   -       -      -      -      -       -      -     -      -      -      -         252,00  -       -        271,58  | 0,00     271,58   | 72,35   72,35
N.Gas       -    -     -     -        -        378,62  -       -      -      -      -       -      -     -      -      -      -         -       793,00  -        1171,62 | 0,00     1171,62  | 239,15  239,15
Biomass     -    -     -     -        -        65,28   -       -      -      -      -       -      -     -      -      -      -         -       -       -        65,28   | 0,00     65,28    | 0,00    0,00
Renewable   -    -     -     -        -        -       -       -      -      -      -       -      3,67  1,95   2,68   -      -         -       -       -        8,31    | 0,00     8,31     | 0,00    0,00
H2 etc.     -    -     -     -        -        -       -       -      -      -      -       -      -     -      -      -      -         -       -       -        0,00    | 0,00     0,00     | 0,00    0,00
Biofuel     -    -     -     -        -        -       -       -      -      -      -       -      -     -      -      -      -         -       -       -        0,00    | 0,00     0,00     | 0,00    0,00
Nuclear/CCS -    -     -     -        -        -       -       -      -      -      -       -      -     -      -      -      -         -       -       -        0,00    | 0,00     0,00     | 0,00    0,00

Total       -    -     -     -        -        554,88  -       -      -      -      -       -      3,67  1,95   2,68   -      -         252,00  793,00  -        1608,18 | 0,00     1608,18  | 342,76  342,76
```

```
Output specifications        Haven Stad reference, low demand.txt                              The EnergyPLAN model 15.0

                                                         District Heating Production
              Gr.1                  |                     Gr.2                                  |                     Gr.3                                  |      RES specification
           District                 | District                                        Stor- Ba- | District                                        Stor- Ba- | RES1  RES2    RES3     RES    Total
           heating Solar CSHP DHP   | heating Solar CSHP CHP  HP   ELT  Boiler EH    age  lance | heating Solar CSHP CHP  HP   ELT  Boiler EH    age  lance | Wind  Offshoı Photo \  4-7 ic
           kW      kW    kW   kW    | kW      kW    kW   kW   kW   kW   kW     kW    kW   kW    | kW      kW    kW   kW   kW   kW   kW     kW    kW   kW    | kW    kW      kW       kW     kW

January    0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 395   288     103      0      786
February   0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 594   409     107      0      1110
March      0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 520   370     256      0      1145
April      0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 312   251     317      0      880
May        0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 249   215     352      0      816
June       0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 376   282     351      0      1009
July       0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 293   233     326      0      851
August     0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 249   202     311      0      762
September  0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 335   243     241      0      820
October    0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 600   420     157      0      1176
November   0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 432   316     92       0      840
December   0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 670   442     42       0      1154

Average    0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 418   306     222      0      945
Maximum    0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 1520  800     1550     0      3691
Minimum    0       0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0       0     0    0    0    0    0      0     0    0     | 0     0       0        0      0

Total for the whole year
GWh/year   0,00    0,00  0,00 0,00  | 0,00    0,00  0,00 0,00 0,00 0,00 0,00   0,00       0,00  | 0,00    0,00  0,00 0,00 0,00 0,00 0,00   0,00       0,00  | 3,67  2,68    1,95     0,00   8,31

Own use of heat from industrial CHP:  0,00 GWh/year
```

```
                                                                                   NATURAL GAS EXCHANGE
ANNUAL COSTS    (1000 EUR)                          DHP &    CHP2   PP     Indi-   Trans  Indu.  Demand   Bio-  Syn-  CO2Hy  SynHy  SynHy  Stor-  Sum      Im-      Ex-
Total Fuel ex Ngas exchange  =     0                Boilers  CHP3   CAES   vidual  port   Var.   Sum      gas   gas   gas    gas    gas    age               port     port
Uranium     =             0                         kW       kW     kW     kW      kW     kW     kW       kW    kW    kW     kW     kW     kW     kW       kW       kW
Coal        =             0
FuelOil     =             0              January    0        0      47017  152876  0      0      199893   0     0     0      0      0      0      199893   199893   0
Gasoil/Diesel=            0              February   0        0      47258  144498  0      0      191756   0     0     0      0      0      0      191756   191756   0
Petrol/JP   =             0              March      0        0      44935  124490  0      0      169425   0     0     0      0      0      0      169425   169425   0
Gas handling =            0              April      0        0      41425  93008   0      0      134434   0     0     0      0      0      0      134434   134434   0
Biomass     =             0              May        0        0      40672  60967   0      0      101639   0     0     0      0      0      0      101639   101639   0
Food income  =            0              June       0        0      40345  44574   0      0      84919    0     0     0      0      0      0      84919    84919    0
Waste       =             0              July       0        0      40986  36187   0      0      77173    0     0     0      0      0      0      77173    77173    0
                                         August     0        0      38714  37498   0      0      76212    0     0     0      0      0      0      76212    76212    0
Total Ngas Exchange costs =        0     September  0        0      40989  52838   0      0      93827    0     0     0      0      0      0      93827    93827    0
                                         October    0        0      42111  82141   0      0      124253   0     0     0      0      0      0      124253   124253   0
Marginal operation costs  =        0     November   0        0      46213  115905  0      0      162118   0     0     0      0      0      0      162118   162118   0
                                         December   0        0      46735  140082  0      0      186817   0     0     0      0      0      0      186817   186817   0
Total Electricity exchange =       0
Import      =             0              Average    0        0      43104  90278   0      0      133381   0     0     0      0      0      0      133381   133381   0
Export      =             0              Maximum    0        0      68979  160546  0      0      229525   0     0     0      0      0      0      229525   229525   0
Bottleneck  =             0              Minimum    0        0      24104  32516   0      0      58245    0     0     0      0      0      0      58245    58245    0
Fixed imp/ex=             0
                                         Total for the whole year
Total CO2 emission costs =         0     GWh/year   0,00     0,00   378,62 793,00  0,00   0,00   1171,62  0,00  0,00  0,00   0,00   0,00   0,00   1171,62  1171,62  0,00

Total variable costs  =            0
Fixed operation costs =            0

Annual Investment costs =          0

TOTAL ANNUAL COSTS  =              0

RES Share:     4,6  Percent of Primary Energy     3,2  Percent of Electricity          8,3  GWh electricity from RES                                    15-september-2020 [16:26]
```

Figure 23 - The output document of EnergyPLAN for the reference design with low/flexible energy demand.



Input Haven Stad all-electric, low demand.txt The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,03
Fixed demand	0,23	Fixed imp/exp.	0,00
Electric heating + HP	0,20	Transportation	0,08
Electric cooling	0,00	Total	0,54

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	0,00	0,00
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	0,00	0,00

					Grid stabili-sation share
Wind	70 MW	0,08	TWh/year	0,00	
Offshore Wind	118 MW	0,32	TWh/year	0,00	
Photo Voltaic	111 MW	0,13	TWh/year	0,00	
Wave Power	0 MW	0	TWh/year	0,00	
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0,25	0,70	
Heat Pump	0	0			3,50
Boiler		0		0,90	
Group 3:					
CHP	0	0	0,25	0,70	
Heat Pump	0	0			3,50
Boiler		0		0,90	
Condensing	97		0,30		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	0,00	0,00

Regulation Strategy: Technical regulation no. 2
CEEP regulation 234570000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : Price_DKV_2005.txt
Addition factor 0,00 DKK/MWh
Multiplication factor 0,00
Dependency factor 0,00 DKK/MWh pr. MW
Average Market Price 0 DKK/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0,40	
Hydro Turbine:	0		0,40	
Electrol. Gr.2:	0	0	0,80	0,15
Electrol. Gr.3:	0	0	0,80	0,15
Electrol. trans.:	0	0	0,85	
Ely. MicroCHP:	0	0	0,85	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	0,00
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output

	District Heating										Electricity																		Exchange	
	Demand	Production									Consumption						Production							Balance					Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million DKK	Exp
January	0	0	0	0	0	0	0	0	0	0	29	12	38	0	0	0	0	61	0	0	0	0	16	100	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	29	12	39	0	0	0	0	78	0	0	0	0	8	100	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	28	12	33	0	0	0	0	73	0	0	0	0	1	100	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	25	12	26	0	0	0	0	64	0	0	0	0	3	100	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	25	12	20	0	0	0	0	59	0	0	0	0	0	100	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	25	12	9	0	0	0	0	47	0	0	0	0	0	100	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	25	12	9	0	0	0	0	49	0	0	0	0	0	100	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	23	12	9	0	0	0	0	45	0	0	0	0	0	100	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	25	12	14	0	0	0	0	48	0	0	0	0	2	100	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	26	12	21	0	0	0	0	64	0	0	0	0	0	100	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	28	12	28	0	0	0	0	62	0	0	0	0	6	100	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	29	12	33	0	0	0	0	70	0	0	0	0	9	100	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	27	12	23	0	0	0	0	60	0	0	0	0	4	100	0	0	0	0	Average price	
Maximum	0	0	0	0	0	0	0	0	0	0	43	80	98	0	0	0	0	224	0	0	0	0	97	100	0	0	0	0	(DKK/MWh)	
Minimum	0	0	0	0	0	0	0	0	0	0	14	0	8	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,23	0,10	0,20	0,00	0,00	0,00	0,00	0,53	0,00	0,00	0,00	0,00	0,03		0,00	0,00	0,00	0,00	0	0

FUEL BALANCE (TWh/year):	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biomass	-	-	-	-	-	0,11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,11	0,00	0,11	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	0,08	0,13	0,32	-	-	-	-	-	0,53	0,00	0,53	0,00	0,00
H2 etc.	-	-	-	-	-	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	-	-	-	-	0,11	-	-	-	-	-	-	0,08	0,13	0,32	-	-	-	-	-	0,64	0,00	0,64	0,00	0,00

Output specifications Haven Stad all-electric, low demand.txt The EnergyPLAN model 15.0

District Heating Production

	Gr.1				Gr.2										Gr.3										RES specification				
	District heating MW	Solar MW	CSHP MW	DHP MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	RES1 Wind MW	RES2 Offshoı MW	RES3 Photo \ MW	RES 4-7 ic MW	Total MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	40	7	0	61
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	55	8	0	78
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	45	18	0	73
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10	32	22	0	64
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	27	24	0	59
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	22	22	0	47
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	22	22	0	49
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	20	20	0	45
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	26	17	0	48
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	44	11	0	64
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	42	7	0	62
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	55	3	0	70
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	36	15	0	60
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	118	111	0	224
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,08	0,32	0,13	0,00	0,53

Own use of heat from industrial CHP: 0,00 TWh/year

ANNUAL COSTS (Million DKK)
Total Fuel ex Ngas exchange = 0
Uranium = 0
Coal = 0
FuelOil = 0
Gasoil/Diesel= 0
Petrol/JP = 0
Gas handling = 0
Biomass = 0
Food income = 0
Waste = 0

Total Ngas Exchange costs = 0

Marginal operation costs = 0

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 0
Fixed operation costs = 0

Annual Investment costs = 0

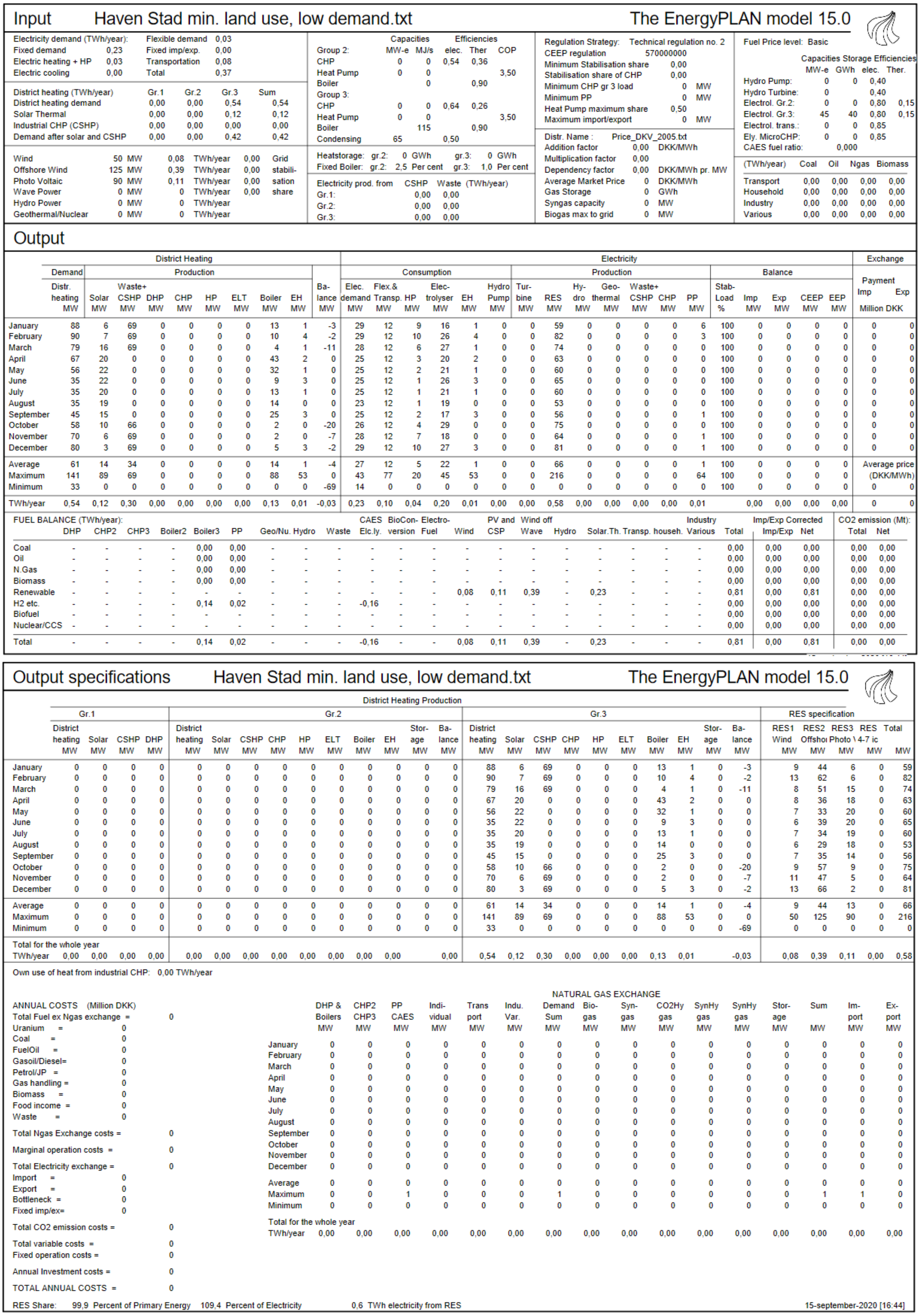
TOTAL ANNUAL COSTS = 0

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

RES Share: 100,0 Percent of Primary Energy 167,3 Percent of Electricity 0,6 TWh electricity from RES 15-september-2020 [16:35]

Figure 24 - The output document of EnergyPLAN for the sll-electric design with low/flexible energy demand.



Input Haven Stad min. land use, low demand.txt — The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,03
Fixed demand	0,23	Fixed imp/exp.	0,00
Electric heating + HP	0,03	Transportation	0,08
Electric cooling	0,00	Total	0,37

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	0,54	0,54
Solar Thermal	0,00	0,00	0,12	0,12
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	0,42	0,42

Wind	50 MW	0,08	TWh/year	0,00	Grid
Offshore Wind	125 MW	0,39	TWh/year	0,00	stabili-
Photo Voltaic	90 MW	0,11	TWh/year	0,00	sation
Wave Power	0 MW	0	TWh/year	0,00	share
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0,54	0,36	
Heat Pump	0	0			3,50
Boiler		0		0,90	
Group 3:					
CHP	0	0	0,64	0,26	
Heat Pump	0	0			3,50
Boiler		115		0,90	
Condensing	65		0,50		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	0,00	0,00

Regulation Strategy: Technical regulation no. 2
CEEP regulation 570000000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : Price_DKV_2005.txt
Addition factor 0,00 DKK/MWh
Multiplication factor 0,00
Dependency factor 0,00 DKK/MWh pr. MW
Average Market Price 0 DKK/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities	Storage	Efficiencies	
	MW-e	GWh	elec.	Ther.
Hydro Pump:	0	0	0,40	
Hydro Turbine:	0		0,40	
Electrol. Gr.2:	0	0	0,80	0,15
Electrol. Gr.3:	45	40	0,80	0,15
Electrol. trans.:	0	0	0,85	
Ely. MicroCHP:	0	0	0,85	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	0,00
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output

	District Heating										Electricity																			Exchange	
	Demand	Production									Consumption						Production							Balance						Payment	
	Distr. heating MW	Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba- lance MW	Elec. demand MW	Flex.& Transp. MW	HP MW	Elec- trolyser MW	EH MW	Hydro Pump MW	Tur- bine MW	RES MW	Hy- dro MW	Geo- thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Stab- Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Imp Million DKK	Exp
January	88	6	69	0	0	0	0	13	1	-3	29	12	9	16	1	0	0	59	0	0	0	0	6	100	0	0	0	0	0	0
February	90	7	69	0	0	0	0	10	4	-2	29	12	10	26	4	0	0	82	0	0	0	0	3	100	0	0	0	0	0	0
March	79	16	69	0	0	0	0	4	1	-11	28	12	6	27	1	0	0	74	0	0	0	0	0	100	0	0	0	0	0	0
April	67	20	0	0	0	0	0	43	2	0	25	12	3	20	2	0	0	63	0	0	0	0	0	100	0	0	0	0	0	0
May	56	22	0	0	0	0	0	32	1	0	25	12	2	21	1	0	0	60	0	0	0	0	0	100	0	0	0	0	0	0
June	35	22	0	0	0	0	0	9	3	0	25	12	1	26	3	0	0	65	0	0	0	0	0	100	0	0	0	0	0	0
July	35	20	0	0	0	0	0	13	1	0	25	12	1	21	1	0	0	60	0	0	0	0	0	100	0	0	0	0	0	0
August	35	19	0	0	0	0	0	14	0	0	23	12	1	19	0	0	0	53	0	0	0	0	0	100	0	0	0	0	0	0
September	45	15	0	0	0	0	0	25	3	0	25	12	2	17	3	0	0	56	0	0	0	0	1	100	0	0	0	0	0	0
October	58	10	66	0	0	0	0	2	0	-20	26	12	4	29	0	0	0	75	0	0	0	0	0	100	0	0	0	0	0	0
November	70	6	69	0	0	0	0	2	0	-7	28	12	7	18	0	0	0	64	0	0	0	0	1	100	0	0	0	0	0	0
December	80	3	69	0	0	0	0	5	3	-2	29	12	10	27	3	0	0	81	0	0	0	0	1	100	0	0	0	0	0	0
Average	61	14	34	0	0	0	0	14	1	-4	27	12	5	22	1	0	0	66	0	0	0	0	1	100	0	0	0	0	Average price	
Maximum	141	89	69	0	0	0	0	88	53	0	43	77	20	45	53	0	0	216	0	0	0	0	64	100	0	0	0	0	(DKK/MWh)	
Minimum	33	0	0	0	0	0	0	0	0	-69	14	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
TWh/year	0,54	0,12	0,30	0,00	0,00	0,00	0,00	0,13	0,01	-0,03	0,23	0,10	0,04	0,20	0,01	0,00	0,00	0,58	0,00	0,00	0,00	0,00	0,01		0,00	0,00	0,00	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon- version	Electro- Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	-	-	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
N.Gas	-	-	-	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biomass	-	-	-	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	0,08	0,11	0,39	-	0,23	-	-	-	0,81	0,00	0,81	0,00	0,00
H2 etc.	-	-	-	-	0,14	0,02	-	-	-	-0,16	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	-	-	-	0,14	0,02	-	-	-	-0,16	-	-	0,08	0,11	0,39	-	0,23	-	-	-	0,81	0,00	0,81	0,00	0,00

Output specifications Haven Stad min. land use, low demand.txt — The EnergyPLAN model 15.0

District Heating Production

	Gr.1				Gr.2										Gr.3										RES specification				
	District heating MW	Solar MW	CSHP MW	DHP MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor- age MW	Ba- lance MW	District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor- age MW	Ba- lance MW	RES1 Wind MW	RES2 Offshoı MW	RES3 Photo \ MW	RES 4-7 ic MW	Total MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	88	6	69	0	0	0	13	1	0	-3	9	44	6	0	59
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90	7	69	0	0	0	10	4	0	-2	13	62	6	0	82
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	79	16	69	0	0	0	4	1	0	-11	8	51	15	0	74
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	67	20	0	0	0	0	43	2	0	0	8	36	18	0	63
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	56	22	0	0	0	0	32	1	0	0	7	33	20	0	60
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	22	0	0	0	0	9	3	0	0	6	39	20	0	65
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	20	0	0	0	0	13	1	0	0	7	34	19	0	60
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	35	19	0	0	0	0	14	0	0	0	6	29	18	0	53
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	45	15	0	0	0	0	25	3	0	0	7	35	14	0	56
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	10	66	0	0	0	2	0	0	-20	9	57	9	0	75
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	70	6	69	0	0	0	2	0	0	-7	11	47	5	0	64
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	80	3	69	0	0	0	5	3	0	-2	13	66	2	0	81
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61	14	34	0	0	0	14	1	0	-4	9	44	13	0	66
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	141	89	69	0	0	0	88	53	0	0	50	125	90	0	216
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33	0	0	0	0	0	0	0	0	-69	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,54	0,12	0,30	0,00	0,00	0,00	0,13	0,01		-0,03	0,08	0,39	0,11	0,00	0,58

Own use of heat from industrial CHP: 0,00 TWh/year

ANNUAL COSTS (Million DKK)
Total Fuel ex Ngas exchange = 0
Uranium = 0
Coal = 0
FuelOil = 0
Gasoil/Diesel= 0
Petrol/JP = 0
Gas handling = 0
Biomass = 0
Food income = 0
Waste = 0

Total Ngas Exchange costs = 0

Marginal operation costs = 0

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 0
Fixed operation costs = 0

Annual Investment costs = 0

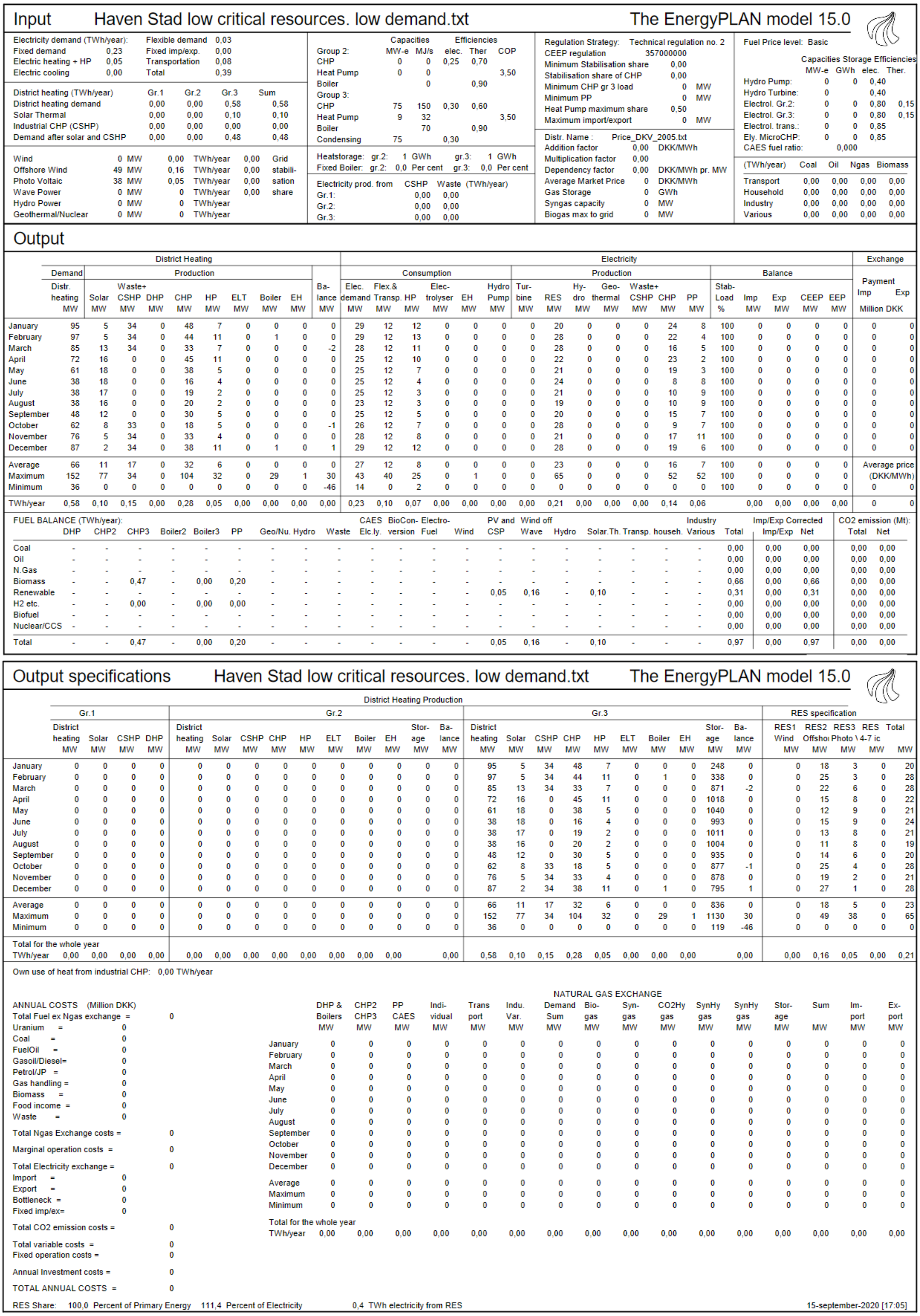
TOTAL ANNUAL COSTS = 0

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi- vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio- gas MW	Syn- gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor- age MW	Sum MW	Im- port MW	Ex- port MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

RES Share: 99,9 Percent of Primary Energy 109,4 Percent of Electricity 0,6 TWh electricity from RES 15-september-2020 [16:44]

Figure 25 - The output document of EnergyPLAN for the minimum land use design with low/flexible energy demand.

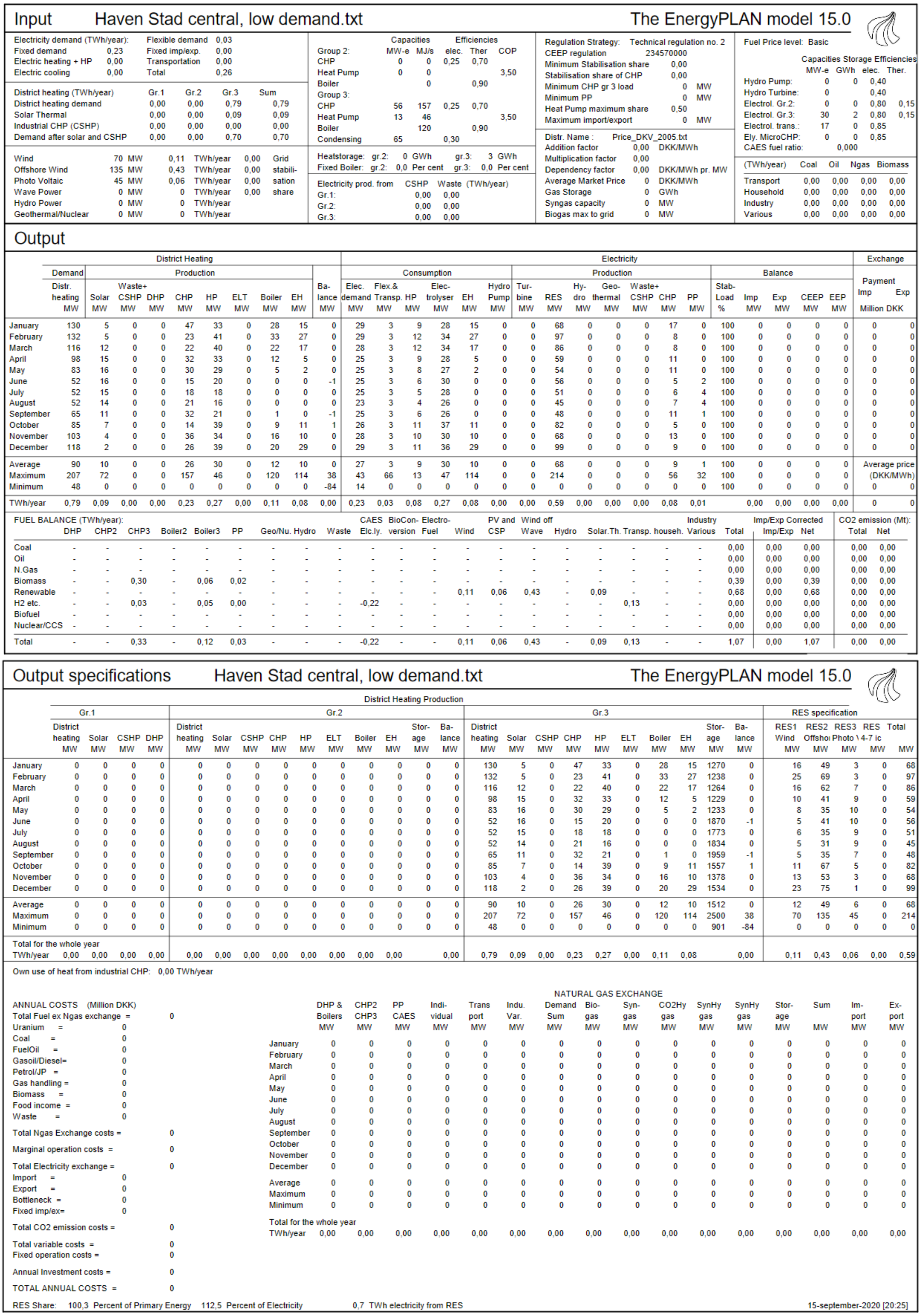


```
Input        Haven Stad low critical resources. low demand.txt                    The EnergyPLAN model 15.0

Electricity demand (TWh/year):      Flexible demand   0,03
Fixed demand              0,23      Fixed imp/exp.    0,00
Electric heating + HP     0,05      Transportation    0,08
Electric cooling          0,00      Total             0,39

District heating (TWh/year)         Gr.1    Gr.2    Gr.3    Sum
District heating demand             0,00    0,00    0,58    0,58
Solar Thermal                       0,00    0,00    0,10    0,10
Industrial CHP (CSHP)               0,00    0,00    0,00    0,00
Demand after solar and CSHP         0,00    0,00    0,48    0,48

Wind                  0  MW     0,00  TWh/year   0,00   Grid
Offshore Wind        49  MW     0,16  TWh/year   0,00   stabili-
Photo Voltaic        38  MW     0,05  TWh/year   0,00   sation
Wave Power            0  MW        0  TWh/year   0,00   share
Hydro Power           0  MW        0  TWh/year
Geothermal/Nuclear    0  MW        0  TWh/year

                      Capacities        Efficiencies
Group 2:              MW-e   MJ/s    elec.  Ther   COP
CHP                      0      0    0,25   0,70
Heat Pump                0      0                  3,50
Boiler                          0           0,90
Group 3:
CHP                     75    150    0,30   0,60
Heat Pump                9     32                  3,50
Boiler                         70           0,90
Condensing              75           0,30

Heatstorage:   gr.2:    1  GWh        gr.3:    1  GWh
Fixed Boiler:  gr.2:  0,0  Per cent   gr.3:  0,0  Per cent

Electricity prod. from      CSHP   Waste  (TWh/year)
Gr.1:                       0,00   0,00
Gr.2:                       0,00   0,00
Gr.3:                       0,00   0,00

Regulation Strategy:    Technical regulation no. 2
CEEP regulation                 357000000
Minimum Stabilisation share          0,00
Stabilisation share of CHP           0,00
Minimum CHP gr 3 load                   0   MW
Minimum PP                              0   MW
Heat Pump maximum share              0,50
Maximum import/export                   0   MW

Distr. Name :        Price_DKV_2005.txt
Addition factor          0,00   DKK/MWh
Multiplication factor    0,00
Dependency factor        0,00   DKK/MWh pr. MW
Average Market Price        0   DKK/MWh
Gas Storage                 0   GWh
Syngas capacity             0   MW
Biogas max to grid          0   MW

Fuel Price level:  Basic

                    Capacities Storage Efficiencies
                     MW-e     GWh    elec.   Ther.
Hydro Pump:             0       0    0,40
Hydro Turbine:          0            0,40
Electrol. Gr.2:         0       0    0,80    0,15
Electrol. Gr.3:         0       0    0,80    0,15
Electrol. trans.:       0       0    0,85
Ely. MicroCHP:          0       0    0,85
CAES fuel ratio:          0,000

(TWh/year)     Coal    Oil     Ngas    Biomass
Transport      0,00    0,00    0,00    0,00
Household      0,00    0,00    0,00    0,00
Industry       0,00    0,00    0,00    0,00
Various        0,00    0,00    0,00    0,00
```

```
Output

                                    District Heating                                |                                       Electricity                                                     | Exchange
           Demand |                     Production                       |          |         Consumption                    |              Production                  |        Balance              |
           Distr. |       Waste+                                         | Ba-      | Elec.  Flex.&        Elec-        Hydro| Tur-        Hy-   Geo-   Waste+              | Stab-                       | Payment
           heating| Solar CSHP  DHP   CHP   HP    ELT   Boiler  EH       | lance    | demand Transp. HP   trolyser  EH   Pump | bine  RES   dro   thermal CSHP  CHP   PP   | Load  Imp  Exp  CEEP  EEP   | Imp      Exp
            MW    | MW    MW    MW    MW    MW    MW    MW      MW       | MW       | MW     MW      MW   MW        MW   MW   | MW    MW    MW    MW      MW    MW    MW   | %     MW   MW   MW    MW    | Million DKK
January      95      5    34     0    48     7     0     0       0          0         29     12     12     0        0     0      0    20     0      0      0    24     8     100    0    0     0     0      0        0
February     97      5    34     0    44    11     0     1       0          0         29     12     13     0        0     0      0    28     0      0      0    22     4     100    0    0     0     0      0        0
March        85     13    34     0    33     7     0     0       0         -2         28     12     11     0        0     0      0    28     0      0      0    16     5     100    0    0     0     0      0        0
April        72     16     0     0    45    11     0     0       0          0         25     12     10     0        0     0      0    22     0      0      0    23     2     100    0    0     0     0      0        0
May          61     18     0     0    38     5     0     0       0          0         25     12      7     0        0     0      0    21     0      0      0    19     3     100    0    0     0     0      0        0
June         38     18     0     0    16     4     0     0       0          0         25     12      4     0        0     0      0    24     0      0      0     8     8     100    0    0     0     0      0        0
July         38     17     0     0    19     2     0     0       0          0         25     12      3     0        0     0      0    21     0      0      0    10     9     100    0    0     0     0      0        0
August       38     16     0     0    20     2     0     0       0          0         23     12      3     0        0     0      0    19     0      0      0    10     9     100    0    0     0     0      0        0
September    48     12     0     0    30     5     0     0       0          0         25     12      5     0        0     0      0    20     0      0      0    15     7     100    0    0     0     0      0        0
October      62      8    33     0    18     5     0     0       0         -1         26     12      7     0        0     0      0    28     0      0      0     9     7     100    0    0     0     0      0        0
November     76      5    34     0    33     4     0     0       0          0         28     12      8     0        0     0      0    21     0      0      0    17    11     100    0    0     0     0      0        0
December     87      2    34     0    38    11     0     1       0          1         29     12     12     0        0     0      0    28     0      0      0    19     6     100    0    0     0     0      0        0

Average      66     11    17     0    32     6     0     0       0          0         27     12      8     0        0     0      0    23     0      0      0    16     7     100    0    0     0     0      Average price
Maximum     152     77    34     0   104    32     0    29       1         30         43     40     25     0        1     0      0    65     0      0      0    52    52     100    0    0     0     0       (DKK/MWh)
Minimum      36      0     0     0     0     0     0     0       0        -46         14      0      2     0        0     0      0     0     0      0      0     0     0     100    0    0     0     0      0        0

TWh/year   0,58   0,10  0,15  0,00  0,28  0,05  0,00  0,00    0,00       0,00       0,23   0,10   0,07  0,00     0,00  0,00   0,00  0,21  0,00   0,00   0,00  0,14  0,06         0,00 0,00  0,00  0,00    0        0

FUEL BALANCE (TWh/year):                                                  CAES  BioCon- Electro-        PV and  Wind off                               Industry          Imp/Exp Corrected   CO2 emission (Mt):
             DHP   CHP2   CHP3   Boiler2  Boiler3   PP     Geo/Nu. Hydro  Waste  Elc.ly. version Fuel   Wind   CSP     Wave    Hydro  Solar.Th. Transp. househ. Various  Total  Imp/Exp  Net      Total   Net

Coal          -     -      -       -        -        -       -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00
Oil           -     -      -       -        -        -       -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00
N.Gas         -     -      -       -        -        -       -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00
Biomass       -     -     0,47     -       0,00     0,20     -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,66   0,00    0,66      0,00   0,00
Renewable     -     -      -       -        -        -       -       -      -      -       -      -      -     0,05    0,16     -      0,10      -       -       -      0,31   0,00    0,31      0,00   0,00
H2 etc.       -     -     0,00     -       0,00     0,00     -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00
Biofuel       -     -      -       -        -        -       -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00
Nuclear/CCS   -     -      -       -        -        -       -       -      -      -       -      -      -      -       -       -       -        -       -       -      0,00   0,00    0,00      0,00   0,00

Total         -     -     0,47     -       0,00     0,20     -       -      -      -       -      -      -     0,05    0,16     -      0,10      -       -       -      0,97   0,00    0,97      0,00   0,00
```

```
Output specifications        Haven Stad low critical resources. low demand.txt        The EnergyPLAN model 15.0

                                                   District Heating Production
                 Gr.1                 |                              Gr.2                                   |                              Gr.3                                    |        RES specification
           District                   | District                                             Stor-  Ba-     | District                                              Stor-  Ba-     | RES1  RES2    RES3    RES   Total
           heating Solar CSHP  DHP    | heating Solar CSHP  CHP   HP    ELT   Boiler EH     age    lance   | heating Solar CSHP  CHP   HP    ELT   Boiler  EH     age    lance   | Wind  Offshoı Photo \ 4-7 ic
           MW      MW    MW    MW     | MW      MW    MW    MW    MW    MW    MW     MW     MW     MW      | MW      MW    MW    MW    MW    MW    MW      MW     MW     MW      | MW    MW      MW      MW    MW
January      0      0     0     0        0      0     0     0     0     0     0      0      0      0         95      5    34    48     7     0     0       0     248      0         0    18       3      0    20
February     0      0     0     0        0      0     0     0     0     0     0      0      0      0         97      5    34    44    11     0     1       0     338      0         0    25       3      0    28
March        0      0     0     0        0      0     0     0     0     0     0      0      0      0         85     13    34    33     7     0     0       0     871     -2         0    22       6      0    28
April        0      0     0     0        0      0     0     0     0     0     0      0      0      0         72     16     0    45    11     0     0       0    1018      0         0    15       8      0    22
May          0      0     0     0        0      0     0     0     0     0     0      0      0      0         61     18     0    38     5     0     0       0    1040      0         0    12       9      0    21
June         0      0     0     0        0      0     0     0     0     0     0      0      0      0         38     18     0    16     4     0     0       0     993      0         0    15       9      0    24
July         0      0     0     0        0      0     0     0     0     0     0      0      0      0         38     17     0    19     2     0     0       0    1011      0         0    13       8      0    21
August       0      0     0     0        0      0     0     0     0     0     0      0      0      0         38     16     0    20     2     0     0       0    1004      0         0    11       8      0    19
September    0      0     0     0        0      0     0     0     0     0     0      0      0      0         48     12     0    30     5     0     0       0     935      0         0    14       6      0    20
October      0      0     0     0        0      0     0     0     0     0     0      0      0      0         62      8    33    18     5     0     0       0     877     -1         0    25       4      0    28
November     0      0     0     0        0      0     0     0     0     0     0      0      0      0         76      5    34    33     4     0     0       0     878      0         0    19       2      0    21
December     0      0     0     0        0      0     0     0     0     0     0      0      0      0         87      2    34    38    11     0     1       0     795      1         0    27       1      0    28

Average      0      0     0     0        0      0     0     0     0     0     0      0      0      0         66     11    17    32     6     0     0       0     836      0         0    18       5      0    23
Maximum      0      0     0     0        0      0     0     0     0     0     0      0      0      0        152     77    34   104    32     0    29       1    1130     30         0    49      38      0    65
Minimum      0      0     0     0        0      0     0     0     0     0     0      0      0      0         36      0     0     0     0     0     0       0     119    -46         0     0       0      0     0

Total for the whole year
TWh/year   0,00   0,00  0,00  0,00     0,00   0,00  0,00  0,00  0,00  0,00  0,00   0,00          0,00       0,58   0,10  0,15  0,28  0,05  0,00  0,00    0,00           0,00      0,00  0,16    0,05   0,00  0,21

Own use of heat from industrial CHP:  0,00 TWh/year

                                                                                                  NATURAL GAS EXCHANGE
ANNUAL COSTS    (Million DKK)                    DHP &    CHP2   PP     Indi-   Trans  Indu.  Demand  Bio-  Syn-  CO2Hy  SynHy  SynHy  Stor-  Sum   Im-   Ex-
Total Fuel ex Ngas exchange =       0            Boilers  CHP3   CAES   vidual  port   Var.   Sum     gas   gas   gas    gas    gas    age          port  port
Uranium      =          0                        MW       MW     MW     MW      MW     MW     MW      MW    MW    MW     MW     MW     MW     MW    MW    MW
Coal         =          0             January     0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
FuelOil      =          0             February    0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Gasoil/Diesel=          0             March       0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Petrol/JP    =          0             April       0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Gas handling =          0             May         0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Biomass      =          0             June        0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Food income  =          0             July        0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Waste        =          0             August      0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Total Ngas Exchange costs =         0 September   0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
                                      October     0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Marginal operation costs  =         0 November    0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Total Electricity exchange =        0 December    0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Import       =          0
Export       =          0             Average     0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Bottleneck   =          0             Maximum     0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0
Fixed imp/ex=           0             Minimum     0        0      0      0       0      0      0       0     0     0      0      0      0      0     0     0

Total CO2 emission costs =          0 Total for the whole year
                                      TWh/year   0,00     0,00   0,00   0,00    0,00   0,00   0,00    0,00  0,00  0,00   0,00   0,00   0,00   0,00  0,00  0,00
Total variable costs  =             0
Fixed operation costs =             0

Annual Investment costs =           0

TOTAL ANNUAL COSTS  =               0

RES Share:   100,0  Percent of Primary Energy   111,4  Percent of Electricity        0,4  TWh electricity from RES                         15-september-2020 [17:05]
```

Figure 26 - The output document of EnergyPLAN for the low critical resources design with low/flexible energy demand.



Input Haven Stad central, low demand.txt The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,03
Fixed demand	0,23	Fixed imp/exp.	0,00
Electric heating + HP	0,00	Transportation	0,00
Electric cooling	0,00	Total	0,26

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	0,79	0,79
Solar Thermal	0,00	0,00	0,09	0,09
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	0,70	0,70

					Grid stabili-sation share
Wind	70 MW	0,11	TWh/year	0,00	
Offshore Wind	135 MW	0,43	TWh/year	0,00	
Photo Voltaic	45 MW	0,06	TWh/year	0,00	
Wave Power	0 MW	0	TWh/year	0,00	
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities MW-e	Capacities MJ/s	Efficiencies elec.	Efficiencies Ther	COP
Group 2:					
CHP	0	0	0,25	0,70	
Heat Pump	0	0			3,50
Boiler		0		0,90	
Group 3:					
CHP	56	157	0,25	0,70	
Heat Pump	13	46			3,50
Boiler		120		0,90	
Condensing	65		0,30		

Heatstorage: gr.2: 0 GWh gr.3: 3 GWh
Fixed Boiler: gr.2: 0,0 Per cent gr.3: 0,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	0,00	0,00

Regulation Strategy: Technical regulation no. 2
CEEP regulation 234570000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : Price_DKV_2005.txt
Addition factor 0,00 DKK/MWh
Multiplication factor 0,00
Dependency factor 0,00 DKK/MWh pr. MW
Average Market Price 0 DKK/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Efficiencies Ther.
Hydro Pump:	0	0	0,40	
Hydro Turbine:	0		0,40	
Electrol. Gr.2:	0	0	0,80	0,15
Electrol. Gr.3:	30	2	0,80	0,15
Electrol. trans.:	17	0	0,85	
Ely. MicroCHP:	0	0	0,85	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	0,00
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output

	District Heating Demand Distr. heating MW	DH Production Solar MW	DH Production Waste+ CSHP MW	DH Production DHP MW	DH Production CHP MW	DH Production HP MW	DH Production ELT MW	DH Production Boiler MW	DH Production EH MW	Ba-lance MW	Electricity Consumption Elec. demand MW	Consumption Flex.& Transp. MW	Consumption HP MW	Consumption Elec-trolyser MW	Consumption EH MW	Consumption Hydro Pump MW	Electricity Production Tur-bine MW	Production RES MW	Production Hy-dro MW	Production Geo-thermal MW	Production Waste+ CSHP MW	Production CHP MW	Production PP MW	Balance Stab-Load %	Balance Imp MW	Balance Exp MW	Balance CEEP MW	Balance EEP MW	Exchange Payment Imp Million DKK	Exchange Payment Exp Million DKK
January	130	5	0	0	47	33	0	28	15	0	29	3	9	28	15	0	0	68	0	0	0	17	0	100	0	0	0	0	0	0
February	132	5	0	0	23	41	0	33	27	0	29	3	12	34	27	0	0	97	0	0	0	8	0	100	0	0	0	0	0	0
March	116	12	0	0	22	40	0	22	17	0	28	3	12	34	17	0	0	86	0	0	0	8	0	100	0	0	0	0	0	0
April	98	15	0	0	32	33	0	12	5	0	25	3	9	28	5	0	0	59	0	0	0	11	0	100	0	0	0	0	0	0
May	83	16	0	0	30	29	0	5	2	0	25	3	8	27	2	0	0	54	0	0	0	11	0	100	0	0	0	0	0	0
June	52	16	0	0	15	20	0	0	0	-1	25	3	6	30	0	0	0	56	0	0	0	5	2	100	0	0	0	0	0	0
July	52	15	0	0	18	18	0	0	0	0	25	3	5	28	0	0	0	51	0	0	0	6	4	100	0	0	0	0	0	0
August	52	14	0	0	21	16	0	0	0	0	23	3	4	26	0	0	0	45	0	0	0	7	4	100	0	0	0	0	0	0
September	65	11	0	0	32	21	0	1	0	-1	25	3	6	26	0	0	0	48	0	0	0	11	1	100	0	0	0	0	0	0
October	85	7	0	0	14	39	0	9	11	1	26	3	11	37	11	0	0	82	0	0	0	5	0	100	0	0	0	0	0	0
November	103	4	0	0	36	34	0	16	10	0	28	3	10	30	10	0	0	68	0	0	0	13	0	100	0	0	0	0	0	0
December	118	2	0	0	26	39	0	20	29	0	29	3	11	36	29	0	0	99	0	0	0	9	0	100	0	0	0	0	0	0
Average	90	10	0	0	26	30	0	12	10	0	27	3	9	30	10	0	0	68	0	0	0	9	1	100	0	0	0	0	Average price	
Maximum	207	72	0	0	157	46	0	120	114	38	43	66	13	47	114	0	0	214	0	0	0	56	32	100	0	0	0	0	(DKK/MWh)	
Minimum	48	0	0	0	0	0	0	0	0	-84	14	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
TWh/year	0,79	0,09	0,00	0,00	0,23	0,27	0,00	0,11	0,08	0,00	0,23	0,03	0,08	0,27	0,08	0,00	0,00	0,59	0,00	0,00	0,00	0,08	0,01		0,00	0,00	0,00	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Imp/Exp Corrected Net	CO2 emission (Mt): Total	CO2 emission (Mt): Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biomass	-	-	0,30	-	0,06	0,02	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,39	0,00	0,39	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	0,11	0,06	0,43	-	0,09	-	-	-	0,68	0,00	0,68	0,00	0,00
H2 etc.	-	-	0,03	-	0,05	0,00	-	-	-	-0,22	-	-	-	-	-	-	-	0,13	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	-	0,33	-	0,12	0,03	-	-	-	-0,22	-	-	0,11	0,06	0,43	-	0,09	0,13	-	-	1,07	0,00	1,07	0,00	0,00

Output specifications Haven Stad central, low demand.txt The EnergyPLAN model 15.0

District Heating Production

	Gr.1 District heating MW	Gr.1 Solar MW	Gr.1 CSHP MW	Gr.1 DHP MW	Gr.2 District heating MW	Gr.2 Solar MW	Gr.2 CSHP MW	Gr.2 CHP MW	Gr.2 HP MW	Gr.2 ELT MW	Gr.2 Boiler MW	Gr.2 EH MW	Gr.2 Stor-age MW	Gr.2 Ba-lance MW	Gr.3 District heating MW	Gr.3 Solar MW	Gr.3 CSHP MW	Gr.3 CHP MW	Gr.3 HP MW	Gr.3 ELT MW	Gr.3 Boiler MW	Gr.3 EH MW	Gr.3 Stor-age MW	Gr.3 Ba-lance MW	RES specification RES1 Wind MW	RES2 Offshoı MW	RES3 Photo \ MW	RES 4-7 ic MW	Total MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	130	5	0	47	33	0	28	15	1270	0	16	49	3	0	68
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	132	5	0	23	41	0	33	27	1238	0	25	69	3	0	97
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	116	12	0	22	40	0	22	17	1264	0	16	62	7	0	86
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	98	15	0	32	33	0	12	5	1229	0	10	41	9	0	59
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	83	16	0	30	29	0	5	2	1233	0	8	35	10	0	54
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	16	0	15	20	0	0	0	1870	-1	5	41	10	0	56
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	15	0	18	18	0	0	0	1773	0	6	35	9	0	51
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	14	0	21	16	0	0	0	1834	0	5	31	9	0	45
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	65	11	0	32	21	0	1	0	1959	-1	5	35	7	0	48
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	85	7	0	14	39	0	9	11	1557	1	11	67	5	0	82
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	103	4	0	36	34	0	16	10	1378	0	13	53	3	0	68
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	118	2	0	26	39	0	20	29	1534	0	23	75	1	0	99
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90	10	0	26	30	0	12	10	1512	0	12	49	6	0	68
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	207	72	0	157	46	0	120	114	2500	38	70	135	45	0	214
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	48	0	0	0	0	0	0	0	901	-84	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00	0,79	0,09	0,00	0,23	0,27	0,00	0,11	0,08		0,00	0,11	0,43	0,06	0,00	0,59

Own use of heat from industrial CHP: 0,00 TWh/year

ANNUAL COSTS (Million DKK)
Total Fuel ex Ngas exchange = 0
Uranium = 0
Coal = 0
FuelOil = 0
Gasoil/Diesel= 0
Petrol/JP = 0
Gas handling = 0
Biomass = 0
Food income = 0
Waste = 0

Total Ngas Exchange costs = 0

Marginal operation costs = 0

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 0
Fixed operation costs = 0

Annual Investment costs = 0

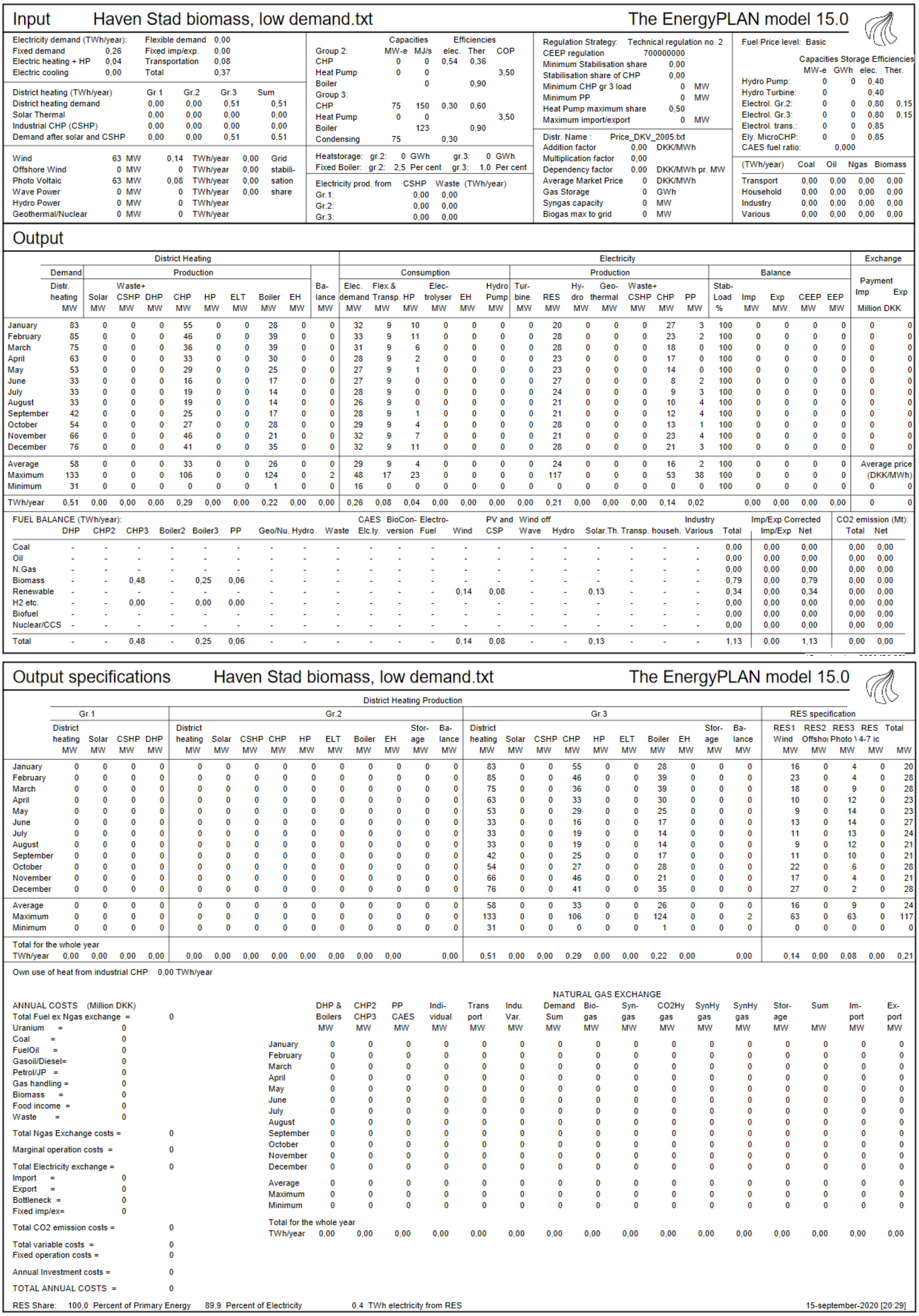
TOTAL ANNUAL COSTS = 0

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

RES Share: 100,3 Percent of Primary Energy 112,5 Percent of Electricity 0,7 TWh electricity from RES 15-september-2020 [20:25]

Figure 27 - The output document of EnergyPLAN for the central design with low/flexible energy demand.



Input Haven Stad biomass, low demand.txt — The EnergyPLAN model 15.0

Electricity demand (TWh/year):		Flexible demand	0,00
Fixed demand	0,26	Fixed imp/exp.	0,00
Electric heating + HP	0,04	Transportation	0,08
Electric cooling	0,00	Total	0,37

District heating (TWh/year)	Gr.1	Gr.2	Gr.3	Sum
District heating demand	0,00	0,00	0,51	0,51
Solar Thermal	0,00	0,00	0,00	0,00
Industrial CHP (CSHP)	0,00	0,00	0,00	0,00
Demand after solar and CSHP	0,00	0,00	0,51	0,51

					Grid stabili-sation share
Wind	63 MW	0,14	TWh/year	0,00	
Offshore Wind	0 MW	0	TWh/year	0,00	
Photo Voltaic	63 MW	0,08	TWh/year	0,00	
Wave Power	0 MW	0	TWh/year	0,00	
Hydro Power	0 MW	0	TWh/year		
Geothermal/Nuclear	0 MW	0	TWh/year		

	Capacities		Efficiencies		
Group 2:	MW-e	MJ/s	elec.	Ther	COP
CHP	0	0	0,54	0,36	
Heat Pump	0	0			3,50
Boiler		0		0,90	
Group 3:					
CHP	75	150	0,30	0,60	
Heat Pump	0	0			3,50
Boiler		123		0,90	
Condensing	75		0,30		

Heatstorage: gr.2: 0 GWh gr.3: 0 GWh
Fixed Boiler: gr.2: 2,5 Per cent gr.3: 1,0 Per cent

Electricity prod. from	CSHP	Waste (TWh/year)
Gr.1:	0,00	0,00
Gr.2:	0,00	0,00
Gr.3:	0,00	0,00

Regulation Strategy: Technical regulation no. 2
CEEP regulation 700000000
Minimum Stabilisation share 0,00
Stabilisation share of CHP 0,00
Minimum CHP gr 3 load 0 MW
Minimum PP 0 MW
Heat Pump maximum share 0,50
Maximum import/export 0 MW

Distr. Name : Price_DKV_2005.txt
Addition factor 0,00 DKK/MWh
Multiplication factor 0,00
Dependency factor 0,00 DKK/MWh pr. MW
Average Market Price 0 DKK/MWh
Gas Storage 0 GWh
Syngas capacity 0 MW
Biogas max to grid 0 MW

Fuel Price level: Basic

	Capacities MW-e	Storage GWh	Efficiencies elec.	Ther.
Hydro Pump:	0	0	0,40	
Hydro Turbine:	0		0,40	
Electrol. Gr.2:	0	0	0,80	0,15
Electrol. Gr.3:	0	0	0,80	0,15
Electrol. trans.:	0	0	0,85	
Ely. MicroCHP:	0	0	0,85	
CAES fuel ratio:		0,000		

(TWh/year)	Coal	Oil	Ngas	Biomass
Transport	0,00	0,00	0,00	0,00
Household	0,00	0,00	0,00	0,00
Industry	0,00	0,00	0,00	0,00
Various	0,00	0,00	0,00	0,00

Output

District Heating

	Demand: Distr. heating MW	Production: Solar MW	Waste+ CSHP MW	DHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Ba-lance MW
January	83	0	0	0	55	0	0	28	0	0
February	85	0	0	0	46	0	0	39	0	0
March	75	0	0	0	36	0	0	39	0	0
April	63	0	0	0	33	0	0	30	0	0
May	53	0	0	0	29	0	0	25	0	0
June	33	0	0	0	16	0	0	17	0	0
July	33	0	0	0	19	0	0	14	0	0
August	33	0	0	0	19	0	0	14	0	0
September	42	0	0	0	25	0	0	17	0	0
October	54	0	0	0	27	0	0	28	0	0
November	66	0	0	0	46	0	0	21	0	0
December	76	0	0	0	41	0	0	35	0	0
Average	58	0	0	0	33	0	0	26	0	0
Maximum	133	0	0	0	106	0	0	124	0	2
Minimum	31	0	0	0	0	0	0	1	0	0
TWh/year	0,51	0,00	0,00	0,00	0,29	0,00	0,00	0,22	0,00	0,00

Electricity

	Consumption: Elec. demand MW	Flex.& Transp. MW	HP MW	Elec-trolyser MW	EH MW	Hydro Pump MW	Production: Tur-bine MW	RES MW	Hy-dro MW	Geo-thermal MW	Waste+ CSHP MW	CHP MW	PP MW	Balance: Stab-Load %	Imp MW	Exp MW	CEEP MW	EEP MW	Exchange Payment Imp Million DKK	Exp
January	32	9	10	0	0	0	0	20	0	0	0	27	3	100	0	0	0	0	0	0
February	33	9	11	0	0	0	0	28	0	0	0	23	2	100	0	0	0	0	0	0
March	31	9	6	0	0	0	0	28	0	0	0	18	0	100	0	0	0	0	0	0
April	28	9	2	0	0	0	0	23	0	0	0	17	0	100	0	0	0	0	0	0
May	27	9	1	0	0	0	0	23	0	0	0	14	0	100	0	0	0	0	0	0
June	27	9	0	0	0	0	0	27	0	0	0	8	2	100	0	0	0	0	0	0
July	28	9	0	0	0	0	0	24	0	0	0	9	3	100	0	0	0	0	0	0
August	26	9	0	0	0	0	0	21	0	0	0	10	4	100	0	0	0	0	0	0
September	28	9	1	0	0	0	0	21	0	0	0	12	4	100	0	0	0	0	0	0
October	29	9	4	0	0	0	0	28	0	0	0	13	1	100	0	0	0	0	0	0
November	32	9	7	0	0	0	0	21	0	0	0	23	4	100	0	0	0	0	0	0
December	32	9	11	0	0	0	0	28	0	0	0	21	3	100	0	0	0	0	0	0
Average	29	9	4	0	0	0	0	24	0	0	0	16	2	100	0	0	0	0	Average price	
Maximum	48	17	23	0	0	0	0	117	0	0	0	53	38	100	0	0	0	0	(DKK/MWh)	
Minimum	16	0	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0	0
TWh/year	0,26	0,08	0,04	0,00	0,00	0,00	0,00	0,21	0,00	0,00	0,00	0,14	0,02		0,00	0,00	0,00	0,00	0	0

FUEL BALANCE (TWh/year):

	DHP	CHP2	CHP3	Boiler2	Boiler3	PP	Geo/Nu.	Hydro	Waste	CAES Elc.ly.	BioCon-version	Electro-Fuel	Wind	PV and CSP	Wind off Wave	Hydro	Solar.Th.	Transp.	househ.	Industry Various	Total	Imp/Exp Corrected Imp/Exp	Net	CO2 emission (Mt): Total	Net
Coal	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
N.Gas	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biomass	-	-	0,48	-	0,25	0,06	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,79	0,00	0,79	0,00	0,00
Renewable	-	-	-	-	-	-	-	-	-	-	-	-	0,14	0,08	-	-	0,13	-	-	-	0,34	0,00	0,34	0,00	0,00
H2 etc.	-	-	0,00	-	0,00	0,00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Biofuel	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Nuclear/CCS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0,00	0,00	0,00	0,00	0,00
Total	-	-	0,48	-	0,25	0,06	-	-	-	-	-	-	0,14	0,08	-	-	0,13	-	-	-	1,13	0,00	1,13	0,00	0,00

Output specifications Haven Stad biomass, low demand.txt — The EnergyPLAN model 15.0

District Heating Production

	Gr.1 District heating MW	Solar MW	CSHP MW	DHP MW	Gr.2 District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		0,00

	Gr.3 District heating MW	Solar MW	CSHP MW	CHP MW	HP MW	ELT MW	Boiler MW	EH MW	Stor-age MW	Ba-lance MW	RES specification: RES1 Wind MW	RES2 Offshoı MW	RES3 Photo \ MW	RES 4-7 ic MW	Total MW
January	83	0	0	55	0	0	28	0	0	0	16	0	4	0	20
February	85	0	0	46	0	0	39	0	0	0	23	0	4	0	28
March	75	0	0	36	0	0	39	0	0	0	18	0	9	0	28
April	63	0	0	33	0	0	30	0	0	0	10	0	12	0	23
May	53	0	0	29	0	0	25	0	0	0	9	0	14	0	23
June	33	0	0	16	0	0	17	0	0	0	13	0	14	0	27
July	33	0	0	19	0	0	14	0	0	0	11	0	13	0	24
August	33	0	0	19	0	0	14	0	0	0	9	0	12	0	21
September	42	0	0	25	0	0	17	0	0	0	11	0	10	0	21
October	54	0	0	27	0	0	28	0	0	0	22	0	6	0	28
November	66	0	0	46	0	0	21	0	0	0	17	0	4	0	21
December	76	0	0	41	0	0	35	0	0	0	27	0	2	0	28
Average	58	0	0	33	0	0	26	0	0	0	16	0	9	0	24
Maximum	133	0	0	106	0	0	124	0	0	2	63	0	63	0	117
Minimum	31	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,51	0,00	0,00	0,29	0,00	0,00	0,22	0,00		0,00	0,14	0,00	0,08	0,00	0,21

Own use of heat from industrial CHP: 0,00 TWh/year

ANNUAL COSTS (Million DKK)
Total Fuel ex Ngas exchange = 0
Uranium = 0
Coal = 0
FuelOil = 0
Gasoil/Diesel= 0
Petrol/JP = 0
Gas handling = 0
Biomass = 0
Food income = 0
Waste = 0

Total Ngas Exchange costs = 0

Marginal operation costs = 0

Total Electricity exchange = 0
Import = 0
Export = 0
Bottleneck = 0
Fixed imp/ex= 0

Total CO2 emission costs = 0

Total variable costs = 0
Fixed operation costs = 0

Annual Investment costs = 0

TOTAL ANNUAL COSTS = 0

NATURAL GAS EXCHANGE

	DHP & Boilers MW	CHP2 CHP3 MW	PP CAES MW	Indi-vidual MW	Trans port MW	Indu. Var. MW	Demand Sum MW	Bio-gas MW	Syn-gas MW	CO2Hy gas MW	SynHy gas MW	SynHy gas MW	Stor-age MW	Sum MW	Im-port MW	Ex-port MW
January	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
February	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
March	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
June	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
July	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
August	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
September	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
October	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
November	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total for the whole year TWh/year	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

RES Share: 100,0 Percent of Primary Energy 89,9 Percent of Electricity 0,4 TWh electricity from RES 15-september-2020 [20:29]

Figure 28 - The output document of EnergyPLAN for the biomass design with low/flexible energy demand.

Appendix D: Footprint of the designs

In this appendix, the footprints of the designs are presented as a complement to the main text in order to clarify the figures and show the values in a more detailed way. The footprint for the three environmental impact categories are presented one by one.

GHG emissions

The lifecycle GHG emissions that are caused by the different designs of the energy supply for Haven-Stad are shown in the table below, for each energy source and/or production technology. Since for wind and solar PV the installed capacity is determining the GHG emissions, rather than the produced energy, the GHG emissions will be based on the potential energy production with the installed capacity (see appendix C). This is because GHG emissions of solar PV and wind turbines occur in the upstream phases rather that during the final energy conversion step. For fossil fuels (in the reference scenario), the actual energy production is used since the emissions are released when burning the fuels.

The table below shows the GHG emissions for each design with the current average energy demand. The second table below shows the same carbon footprint outcomes but for the low/flexible energy demand. The GHG emissions are presented in multiple forms: total emissions, total emissions per person and emissions per kWh energy production.

Table 24 - Lifecycle GHG emission of the different designs for the energy supply system of Haven-Stad with current average energy demand. In kt CO_2-eq./yr unless indicated otherwise.

	Reference	All-electric simple	Min. land use	Low critical resources	Central	Biomass
Coal	41.6	-	-	-	-	-
Oil	7.6	-	-	-	-	-
Natural gas	330.9	-	-	-	-	-
Biomass	2.0	2.67	-	21.42	12.55	25.40
Onshore wind	0.046	2.38	1.875	-	2.375	2
Offshore wind	0.024	5	7.375	2.125	6.125	-
Solar PV	0.129	9.9	8.58	3.3	3.96	5.28
Solar thermal	-	-	4.95	2.25	2.025	3.15
Geothermal heat	-	-	12.95	5.55	-	-
Total	**382.3**	**19.95**	**35.73**	**34.65**	**27.04**	**35.83**
Total (t CO_2-eq./cap./yr)	**3.01**	**0.157**	**0.281**	**0.273**	**0.213**	**0.282**
Carbon intensity electricity (g CO_2/kWh)	**550**	**35**	**27.43**	**53.4**	**28.16**	**53.26**
Emissions from fossil transport fuels	85.3	0	0	0	0	0
Total GHG emission incl. transport	467.6	19.95	35.73	34.65	27.04	35.83

Table 25 - Lifecycle GHG emission of the different designs for the energy supply system of Haven-Stad with low/flexible energy. In kt CO2-eq./yr unless indicated otherwise.

	Reference	All-electric simple	Min. land use	Low critical resources	Central	Biomass
Coal	41.6	-	-	-	-	-
Oil	7.6	-	-	-	-	-
Natural gas	300.8	-	-	-	-	-
Biomass	2.0	2.67	-	20.20	11.93	24.48
Onshore wind	0.046	2.125	1.5	-	2.125	1.875
Offshore wind	0.024	4.875	5.25	2	5.625	-
Solar PV	0.129	9.24	7.26	3.3	3.96	5.28
Solar thermal	-	-	4.95	2.25	2.025	2.93
Geothermal heat	-	-	11.1	5.55	-	-
Total	**352.2**	**18.91**	**30.06**	**33.3**	**25.665**	**34.57**
Total (t CO_2-eq./cap./yr)	**2.77**	**0.149**	**0.236**	**0.262**	**0.202**	**0.272**
Carbon intensity electricity (g CO_2/kWh)	**550**	**34.57**	**24.16**	**52.4**	**27.54**	**52.93**
Emissions from fossil transport fuels	85.3	0	0	0	0	0
Total GHG emission incl. transport	437.5	18.67	30.06	39.53	29.26	34.57

Land use

In the tables below, the land use impacts of the energy systems for Haven-Stad are shown. The first table is calculated with an energy demand that is based on the current average energy demand. The second table below shows the land use footprint for the same designs assuming a lower and partly flexible energy demand. Since for wind and solar PV the installed capacity is determining the land use, rather than the produced energy, the land use footprint will be based on the potential energy production with the installed capacity.

Table 26 - Total land use of the energy in Haven-Stad for the different designs with current average energy demand. In hectare, unless otherwise indicated.

	Reference scenario	All-electric	Minimum land use	Low critical resources	Central	Biomass
Coal	23.20	-	-	-	-	-
Natural gas	442.25	-	-	-	-	-
Biomass	975.97	1639	-	10430	6109	12367
Onshore wind	17.73	917.7	724.5	-	917.7	772.8
Offshore wind	12.94	1932	2849.7	821.1	2366.7	-
Solar PV	3.33	256.5	222.3	85.5	102.6	136.8
Solar thermal	-	-	63.8	29	26.1	40.6
Geothermal	-	-	14	6	-	-
Total	**1475.42**	**4745.2**	**3874.3**	**11371.6**	**9522.1**	**13317.2**
Total (ha/cap.)	**0.0116**	**0.0373**	**0.030**	**0.0894**	**0.075**	**0.1047**

Table 27 - Total land use of the energy in Haven-Stad for the different designs with low/flexible energy demand. In hectare, unless otherwise indicated.

	Reference scenario	All-electric simple	Minimum land use	Low critical resources	Central	Biomass
Coal	23.20	-	-	-	-	-
Natural gas	403.03	-	-	-	-	-
Biomass	975.97	1490	-	9834	5811	11473
Onshore wind	17.73	821.1	579.6	-	821.1	724.5
Offshore wind	12.94	1883.7	2028.6	772.8	2173.5	-
Solar PV	3.33	239.4	188.1	85.5	102.6	136.8
Solar thermal	-	-	63.8	29	26.1	40.6
Geothermal	-	-	12	6	-	-
Total	**1436.2**	**4434.2**	**2872.1**	**10727.3**	**8934.3**	**12374.9**
Total (ha/cap.)	**0.0113**	**0.0349**	**0.0226**	**0.0844**	**0.0703**	**0.0973**

Use of critical resources

The tables below show the material requirement for each design, together with the end use of these materials. The first table shows the use of critical resources for the designs with current average energy demand, the second table show the results based on the low/flexible energy demand.

Table 28 - Use of critical resources in the different design with current average energy demand per energy source. In kg

	Silver (If PV is only c-Si PV)	Tellurium (If PV is only CdTe PV)	Indium (If PV is only CIGS PV)	Neodymium (if wind uses permanent magnets)	Dysprosium (if wind uses permanent magnets)	Lithium (kg/kWh)
Reference design ↓						
Onshore wind	0	0	0	273.6	36.5	0
Offshore wind	0	0	0	144	19.2	0
Solar PV	36.8	97.7	35.7	0	0	0
(B/FC)EVs	0	0	0	0	0	0
Total	**36.8**	**97.7**	**35.7**	**417.6**	**55.7**	**0**
All-electric design ↓						
Onshore wind	0	0	0	14400	1920	0
Offshore wind	0	0	0	21600	2880	0
Solar PV	2850	7560	2760	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	600000
Total	**2850**	**7560**	**2760**	**56155**	**7207**	**834900**
Minimum land use design ↓						
Onshore wind	0	0	0	10800	1440	0
Offshore wind	0	0	0	31500	4200	0
Solar PV	2375	6300	2300	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	600000
Total	**2375**	**6300**	**2300**	**62455**	**8047**	**834900**
Low critical resources design ↓						
Onshore wind	0	0	0	0	0	0
Offshore wind	0	0	0	9000	1200	0
Solar PV	950	2520	920	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	0
Total	**950**	**2520**	**920**	**29155**	**3607**	**234900**
Central design ↓						
Onshore wind	0	0	0	14400	1920	0
Offshore wind	0	0	0	26100	3480	0
Solar PV	1187.5	3150	1150	0	0	0
(B/FC)EVs	0	0	0	20155	2407	0
Battery (if Li-ion)	0	0	0	0	0	0
Total	**1187.5**	**3150**	**1150**	**60655**	**7807**	**0**
Biomass ↓						
Onshore wind	0	0	0	11700	1560	0
Offshore wind	0	0	0	0	0	0
Solar PV	1543.75	4095	1495	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	100000
Total	**1543.75**	**4095**	**1495**	**31855**	**3967**	**334900**

Table 29 - Use of critical resources in the different designs with low/flexible energy demand per energy source. In kg

	Silver (If PV is only c-Si PV)	Tellurium (If PV is only CdTe PV)	Indium (If PV is only CIGS PV)	Neodymium (if wind uses permanent magnets)	Dysprosium (if wind uses permanent magnets)	Lithium (kg/kWh)
Reference design ↓						
Onshore wind	0	0	0	273.6	36.5	0
Offshore wind	0	0	0	144	19.2	0
Solar PV	36.8	97.7	35.7	0	0	0
(B/FC)EVs	0	0	0	0	0	0
Total	**36.8**	**97.7**	**35.7**	**417.6**	**55.7**	**0**
All-electric design ↓						
Onshore wind	0	0	0	12600	1680	0
Offshore wind	0	0	0	20880	2784	0
Solar PV	2612.5	6993	2530	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	500000
Total	**2612.5**	**6993**	**2530**	**53635**	**6871**	**734900**
Minimum land use design ↓						
Onshore wind	0	0	0	9000	1200	0
Offshore wind	0	0	0	22500	3000	0
Solar PV	2137.5	5670	2070	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	540000
Total	**2137.5**	**5670**	**2070**	**51655**	**6607**	**774900**
Low critical resources design ↓						
Onshore wind	0	0	0	0	0	0
Offshore wind	0	0	0	8820	1176	0
Solar PV	902.5	2394	874	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	0
Total	**902.5**	**2394**	**874**	**28975**	**3583**	**234900**
Central design ↓						
Onshore wind	0	0	0	12600	1680	0
Offshore wind	0	0	0	24300	3240	0
Solar PV	1068.75	2835	1035	0	0	0
(B/FC)EVs	0	0	0	20155	2407	0
Battery (if Li-ion)	0	0	0	0	0	0
Total	**1068.75**	**2835**	**1035**	**57055**	**7327**	**0**
Biomass design ↓						
Onshore wind	0	0	0	11340	1512	0
Offshore wind	0	0	0	0	0	0
Solar PV	1496.25	3969	1449	0	0	0
(B/FC)EVs	0	0	0	20155	2407	234900
Battery (if Li-ion)	0	0	0	0	0	60000
Total	**1496.25**	**3969**	**1449**	**31495**	**3919**	**294900**