EnergyNL2050: refining energy demand and renewable sources in 2050
Version December 02, 2022 v 1.2

The EnergyNL2050 energy system analysis refined

Refinement and update of energy demand and renewable resources in 2050.

July 2022

Review CBS and demand

KIVI Electrical Engineering: Loek Boonstra, Steven Luitjens, Koen Huizer, Eric Persoon

For contact: eric.persoon@upcmail.nl

Version history
December 02, 2022: some small textual improvements in de main body and appendix A

Table of content page

Summary

From 2013 to 2017 we, the Activities Group of KIVI EE-Zuid, organized several seminars in Utrecht where more than 50 Dutch professionals presented their views on the energy challenge for the Netherlands in the future. Based on this particularly useful information we devised an energy plan for 2050 and published it beginning 2018 (ref. 1; for references see chapter 10).
The EnergyNL2050 plan describes an energy system which is CO_2 neutral. The system generates more than 85% of the nationally needed energy from solar and wind sources, and needs at most 15% import from abroad. The EnergyNL2050 system is a long-term outlook, focusing on 2050.

The results of detailed simulations using hourly weather data, renewable energy production and demand data for three consecutive years have been reported in 2020 (ref. 3). Functional energy demands from 2015 were extrapolated to the energy demands expected in 2050. From this the required renewable energy could be analyzed and derived.

Feedback on the paper and presentations of the results showed that some assumptions for the energy demand and renewable energy resources in 2050 needed a refinement. This paper describes in more detail the estimate of demand and the options for renewable resources in 2050 based on new insights. Especially the topics of steel production and decarbonization of shipping and aviation are discussed in more detail.

Overall, the changes are minor, and the overall picture stays as discussed in 2020 (ref.3). The total energy demand in 2050 was 338 TWh in the 2020 paper (ref. 3); we now arrive at a demand of 349 TWh (an increase of 2%). The hydrogen needs decrease from 107 to 92 TWh (-15%) and the electricity needs increased from 211 to 237 TWh (+12%). The backup system is 16 TWh electricity requiring 27 TWh hydrogen, the same as the values of the 2020 paper.

Both PV and wind resources increase a few percent to accommodate the different types of demand and the decrease of other renewables, from the more optimistic 20 TWh to the realistic 8 TWh.

Our current refinement also addresses two additional issues.
The Dutch chemical industry currently uses imported fossil oil as feedstock. This must be replaced by a renewable source in 2050. Recycling end-of-live plastics and (imported) biomass are needed.

The EnergyNL2050 plan only considered aviation and ship transport for domestic use. But a substantial amount of fossil fuel is used in (and sold by) the Netherlands for international transport via air and water. Of course, this needs to be decarbonized as well. Hydrogen import is required to cover these needs.

1 Introduction

In 2018 we, the Activities Group of KIVI EE-Zuid, published in the white paper "***EnergyNL2050" the results of our study on a full carbon free Dutch energy system 2050.***

The paper describes an energy system for the Netherlands largely based on solar and wind sources, with a hydrogen backbone, e.g. for storage (ref. 1 Persoon et al. 2017). EnergyNL2050 is one of the systems analyzed by Berenschot in 2018 in the report on system options as input for the Dutch Climate Agreement (Den Ouden et al. 2018, ref. 2).

The plan optimizes a mix of renewable energy sources: wind power onshore and offshore, PV-electricity, some other renewables, and some imported electricity, covering most of the energy demands. Moreover, a rough estimate of the minimal required backup electricity was calculated.

Our 2020 paper ***"Design of a Dutch carbon free energy system, energyNL2050"*** (ref. 3, indicated with "the 2020 paper" in this paper) was an extended version of the 2018 paper, with thorough simulations based on actual data for wind, solar radiation, temperature and electricity demand on an hourly basis. This results in insights about the required capacities for the (short term) one day storage systems and the backup system.

The simulation study also resulted in insight in the required seasonal hydrogen storage and the required hydrogen to cover the demands during periods with low production of the variable renewable energy during cold winter days.

This study was complemented by a financial analysis to obtain an optimal system based on minimal annual energy costs.

We consider this 2020 paper as the final paper on the EnergyNL2050 plan. The feedback on both papers indicates that they lack sufficient explanation in several locations. For this reason, we have written this 3rd supplemental paper to provide improved explanations and some refinement regarding the different calculations.

This supplement paper only concentrates on the energy demand part and the required renewable energy sources covering these demands of the 2020 paper (ref. 3). The simulations and the financial analysis are not discussed in this paper.

These are the specific subjects with improved explanation and some refinements:

Energy demand:

- **Low temperature heat demand** with more explanation for de heat demand in the build environment.
- **High-temperature heat demand (Industrial high-temperature heat) and feedstock demand** with improved explanation and refined calculations for
    - sustainable crude steel processing
    - green ammonia and plastic production
    - decarbonizing the required feedstock
- **Transport energy demand**
    - Improved explanation and refined calculations
    - Decarbonization of international shipping and aviation

Mix of required renewable energy sources:

- **Refinement of "other renewable energy sources"**

Transport and temporary storage of the produced hydrogen:

- **More explanation and refinement.**

This paper is organized as follows:
The next **chapter 2** will start with summarizing the 2020 results (ref. 3).
Chapters 3 and 4 refine the analysis of energy demand and need for energy resources, mainly offshore wind and PV.
The final energy demands for the energy functions are analysed using the CBS energy balance 2015. (Details are given in appendix C).
The special issue of decarbonizing feedstock for the chemical industry and the fuels for international aviation and shipping is part of chapter 3.
The details of the "other renewable energy sources" are described in chapter 4.
Chapter 5 discusses and summarizes the observed differences between what we described in the original paper (ref. 3) and this paper.
Chapter 6 relates the new results to other aspects of the EnergyNL2050 system. These aspects are verification using the time series simulation, the financial analysis and implementation aspects.
Chapter 7 describes (in a qualitative sense) some alternative design options for the energy system, in particular using more import of green hydrogen and nuclear power.
Chapter 8 contains conclusions.
Appendices A, B and C giving more details on the topics in the previous chapters.

2 Compilation of results energy demand and resources of the energyNL2050 system.

In our 2020 paper ***"Design of a Dutch carbon free energy system, energyNL2050"*** (ref. 3) a first estimate of the energy demand and resources was given. In this chapter a compilation of the results which are obtained when switching over from the fossil-based energy demand nowadays to the use of electricity and hydrogen as the only energy carriers of the 2050 demands.

2.1 The energyNL2050 system data from 2020 paper (ref. 3)

In figure 1 the EnergyNL2050 system shows the data of demand and renewable resources.

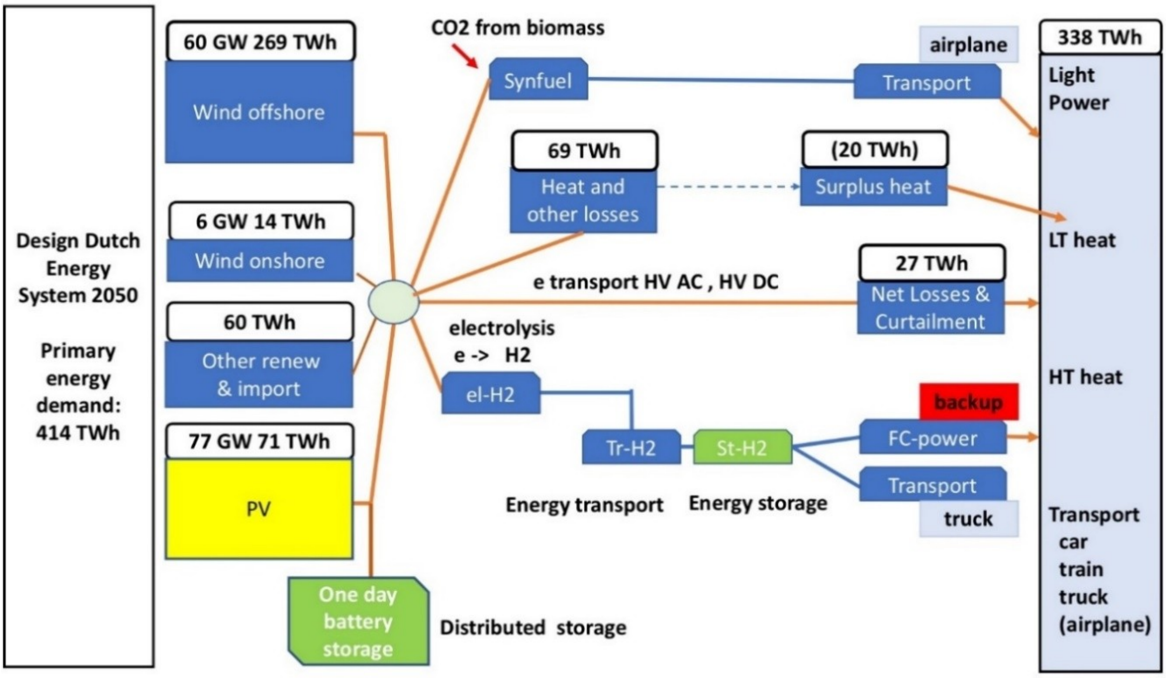


Figure 1 EnergyNL2050 energy system (ref. 3)

The description of our energyNL2050 system is based on the functional energy demand grouping as introduced by CE Delft in their 2014 study (Warringa and Rooijers 2015, ref. 4):

- Basic electrical demand
- Transport
- High-temperature heat (temperatures>100 °C) and
- Low-temperature heat (T<100 °C)

The renewable resources are limited to on- and offshore wind, PV, other renewable resources and some import.

2.2 Energy demand for EnergyNL2050 system in 2020 paper (ref. 3)

Using the 2015 functional energy demands we estimate the demands in 2050 assuming an annual growth of about 1.15%. We also assumed an annual energy saving of 1%, resulting in 2050 demands, slightly higher than the current demands.

This results in the 2050 demands as described in figure 1 and the table 1.

Functional Energy Demand	2015 Fossil based TWh	Electricity TWh	2050 Hydrogen TWh	Heat Nets TWh
Basic electricity demand	120	127		
Transport	160	28	47	
Hydrogen compression (700 bar)		5		
High Temperature Heat	160	26	60	
Low Temperature Heat	200	25		20
Total Demand TWh	**640**	**211**	**107**	**20**

Table 1 Functional energy demands 2050 compared with the 2015 demands (ref. 3)

2.3 Energy resources for EnergyNL2050 system in 2020 paper (ref. 3)

The only energy sources we use are wind power (on- and offshore), solar (PV) power, some import and some possible new renewables, but still in a research phase. In the 2020 paper the following mix of the renewable energy sources follows:

Renewable Energy Sources Mix	Power GW	Energy/year TWh.el	Contribution %	full load hours
1. PV	77	71	17%	920
2. Wind offshore	60	269	65%	4500
3. Wind onshore	6	14	3%	2500
4. Other renewables	2,5	20	5%	8000
5. Import electricity	(variable)	40	10%	
6. Import hydrogen		-		
Total Primary Energy Demand		**414**	**TWh**	

Table 2 The renewable energy sources for the energyNL2050 system ('Other renewables': energy sources still in research phase). In Chapter 3 and 4 the data are refined and updated.

3 The energyNL2050 system analysis refinement of the energy demand in 2015 and 2050

3.1 Introduction

The 2050 energy system design is based on four basic steps:

1. Determination of the final energy demand for the 4 energy functions (Basic Electricity, Low Temperature (LT) heat, High Temperature (HT) heat, Transport) and feed-stock demand for the chosen baseline year: 2015.

2. Estimation of the final energy demand 2050. The analysis is based on the general assumption that most of the sectors will have an annual growth of 1.15%. But we expect also ongoing energy savings of about 1% annually. Due to that in our study the resulting energy demands in 2050 are about the same as the current ones.
3. Determination of the mix of renewable energy sources covering the 2050 final energy demand.
4. The design of the backup system capacity and maximal power, securing that energy will always be delivered the whole year long and including periods with more extreme cold weather conditions. This step requires careful system simulation, based on the use of real, hourly weather and energy demand data.

The verification study explained in detail in the 2020 paper also resulted for the refined data in improved outputs. See the improved high level energy system diagram in appendix A for more information.

3.2 The final energy demand in 2015

As also indicated in our 2020 and 2018 paper the final energy demand in 2015 is derived from the data provided by the Dutch centre for statistics (CBS) (ref. 10). The data are available in great detail for all sectors like industry, energy, households, utilities, agriculture etc. The following paragraphs on energy demand in 2050 refer to these data in more detail.
Our energy system design is based on a functional energy classification (see paragraph 2.1), but we have added the feedstock demand for the chemical industry. Therefore, the CBS data must be regrouped for obtaining the functional energy demands. Particularly for LT-heat and HT-heat regrouping is needed.
In this paper the starting values for the energy functions have been taken from the published CBS Energy Balance. The approach is outlined in Appendix C.
Major conclusions from this new approach applied to our reference year 2015 is that the new starting values are consistent with the values applied in our earlier 2020 and 2018 papers. Results are given in the next sections with additional explanations in appendix B.

3.2.1 Basic electricity demand in 2015

Basic electricity demand covers the electricity required for lighting, ICT and for all electric power devices in all sectors from households to industry.
CBS publishes the final consumption of energy customers (industry, transport and others) broken down into various sub-sectors. In 2015 this was 104 TWh.
The above number excludes 5.5 TWh of electrical network losses, 4.5 TWh of electricity consumed during electricity production and 6 TWh in the other parts of the energy sector. The figure of 6 TWh includes 2.5 TWh during extraction of crude petroleum and gas, 2.5 TWh in Refineries and 0.2 TWh in Cokes Ovens and Blast Furnace for crude steel production.

3.2.2 LT-heat demand in 2015

The low temperature heat demand (Table 3)is used entirely for space heating and hot water demand. Basic sectors for this demand are the households, utility sector, industry, and agriculture.
The demands are derived from the published CBS energy balance 2015. See also appendix B table B 2.1 and B 2.2. Total demand is 175 TWh low temperature heat in 2015.

Low temperature heat demand	2015 TWh heat
Households	88
Utilities	39
Industry	16
Agriculture	26
Some others	6
	+----
Total	**175 TWh**

Table 3 Current (2015) low temperature heat demand

3.2.3 HT-heat and feedstock demand in 2015

The high-temperature energy demand is fully originating from the process industry. Using the CBS data for the energy balance this high-temperature heat demand can be derived for the various sectors:

- **Basic steel:** Current production level is 7.5 Mton crude steel produced with 25% iron scrap. The iron ore after cleaning and first preprocessing is reformed with cokes to crude steel. Steel making is responsible for a serious part of the total domestic CO_2 emission: 12.5 Mton CO_2. About 80% of the produced crude iron is exported.
- **Ammonia**: is produced from Hydrogen and Nitrogen with the Haber-Bosch process. The hydrogen is produced from natural gas by steam cracking, a process responsible for strong CO_2 emission. The ammonia is mainly applied in the fertilizer industry and for a minor part in the chemical industry.
- **Chemical industry:** the chemical industry or plastic industry is based on the C2-C4 olefins: ethylene (C_2H_4), propane (C_3H_6) and butane (C_4H_8) as the basic building blocks. Most dominant is ethylene. Polymerization transforms C2H4 to the well-known plastics as polyethylene, PVC, synthetic rubber, etc. The olefins are produced from naphtha, the lighter hydrocarbon derivatives from the refinery industry. The energy in the produced plastics is not used as fuel and will therefore not be counted in the domestic energy use.
  Current (2015) naphtha-based feed-stock is 114 TWh, about 9 Mton naphtha.
- **Refinery:** Major products from the refinery sector are the transport fuels as diesel, petrol gas and kerosene and naphtha for the plastic industry. Most of the produced fuels are exported via pipelines running from the Rotterdam Botlek area via Venlo to Germany. The fuels as diesel and kerosene are bunkered near the international harbors and Schiphol to be used for the international shipping and air transport. As the combustion-based propulsion in the transport sector, road transport as well the shipping sector will fully chance to electric propulsion (battery based or hydrogen fuel cell based) this refinery sector will ultimately disappear.
- **All others:** This group of high-temperature industrial sectors includes the (sub)sectors like chlorine, food industry, glass production, construction, cement industry etc.

In the next table the resulting demands are summarized and for more information the results are broken down to values for the energetic and non-energetic demands, in our paper indicated as thermal and non-thermal.
Non-thermal energy demands includes: the use of natural gas as feedstock (ammonia), the use of petroleum products as feedstock (plastics), the net energy consumed for transforming coal to cokes and to steel and the net energy consumed in the transforming of crude oil to petroleum products (refineries)

Fossil	**Total TWh**	**Thermal TWh**	**Non-Thermal TWh**
Basic steel	29	11	18
Ammonia:	26	7	19
Chemical industry	55	55	*(114)*
Refinery energy	50	34	16
All others	25	25	
	+----		
Total 2015 HT heat demand:	185 TWh		

Fossil feedstock demand for chemical industry : 114 TWh (Naphtha from the refinery sector

Table 4 The 2015 high-temperature heat demand in the industrial sector. See also appendix B for more explanation

3.2.4 Transport sector energy demand 2015

The fuel demand for the various transport types can perfectly be derived from the CBS 2015 energy balance with the above-mentioned approach. For the total electrical or hydrogen energy, required for a sustainable transport sector, the efficiency of the propulsion systems is estimated and mentioned in the following table:

Transport type energy	TWh (fossil)	TTW/TTProp Efficiency %	wheel (propeller) TWh
Passenger cars:	74	25	19
Lighter road transport:	15	25	3.8
Heavy road transport:	22	35	7.7
Other road transport	10	35	3.5
Fishing and inland shipping:	30	40	12
Inland aviation:	3 TWh kerosene (=0,25 Mton)		
	+-----		
Total transport energy demand 2015: 154 TWh			

Table 5 Energy demand transport sector 2015 including the tank-to-wheel (TTW) efficiency or tank-to-propeller (TTP) efficiency plus the wheel and propeller energy.

3.3 The expected energy demand 2050

Starting point are de current (2015) functional energy demands. Then we assume, that the economy will have some annual economic growth the coming decades up to 2050, with the consequence that energy demands will also grow. This is in line with the Berenschot 2020 study on a climate neutral energy system, the EU controlled scenario (ref. 5). But we may expect that the following aspects will strongly reduce the energy demands (refs. 6-9):

- many improvements in process technology,
- re-use of rest heat,
- re-use and recycling of products and materials,
- improved heat insulation in the build environment.

Full decarbonization has been realized by replacing the current fossil-based fuels with green electricity and hydrogen. See appendix B for additional explanations.

3.3.1 The basic electricity demand 2050

Due to strong improvement of the power equipment and lighting systems during coming decades the basic electricity demand will decrease with an average annual saving of 1%. On the other hand, an ongoing growth especially due to strongly growing demand for cooling and the ICT sector, will largely compensate this energy saving, resulting in a basic electricity demand slightly higher than the 2015 demand: 110 TWh.
The 2050 net losses will be a bit higher, due to the many required DC to AC converters: resulting in 5% net losses. As will be shown in part 4, the 2050 electricity produced by mix of the renewable sources plus some import is 406 TWh, estimating 5% net losses, the 2050 net losses are 20 TWh. See also the energy system block diagram in appendix A. The left upper corner shows the different losses (battery based "One Day Storage" losses, curtailment and the net losses).

3.3.2 Low-Temperature heat demand (LT heat demand) 2050

Considerable LT heat savings are realized by applying the following 3 approaches in the EnergyNL2020 study:

1. Heavy, but affordable insulation measures in the older (built before 2000) houses and buildings, resulting in energy label B or better. This will result in a 25% heat demand saving. This saving ratio may also be applied to the three other sub-sectors: utilities, Industry with low temperature heat demands and agriculture.
2. Using rest heat from the high-temperature industry as a major heat source for the heat nets. In our study rest heat from the electrolysis plants are the major heat sources. The heat nets will grow from the current 6.25 TWh heat to 20 TWh heat in 2050.
3. Using heat pumps as the major central heat system in the building environment. Not only for the private houses but for the larger buildings as well. The heat pumps will have an annual average coefficient of performance (COP) of 4.

A remark should be made: based on recent studies the *hybrid heat pumps* could offer a better, more cost-effective solution for the older-house owners. In such a configuration heat pump with an COP of 4 will produce about 60% (CE-Delft2017, ref. 11) of the heat demand and the other heat for the winter periods will be delivered by the heat boiler, using hydrogen as the gas fuel. The current natural gas network is well appropriate to transport 100% hydrogen, but most of the gas network equipment including heat boilers must be improved for use of the hydrogen gas instead of natural gas (ref 28).

Summarizing the resulting gross energy demand for the LT heat demand 2050 as calculated in appendix B in table Table 6 below.

The required net 130 TWh LT heat demand will be produced by:

- **110 TWh heat from heat pumps, COP=4 requiring 27,5 TWh electricity.** The 110 TWh heat will be delivered from outside air, surface water and ground water sources.
- **20 TWh heat via heat nets with 80% heat efficiency and 5% electricity required for the hot water circulation pumps:** gross heat demand is 25 TWh from hydrogen electrolysis systems and from the hydrogen fuel cell backup power plants., the circulation pumps ask 5% = 1.5 TWh electricity.

Total electricity demand will be: 27.5 + 1.5 = 29 TWh electricity.

	2015		**2050**		
Low temperature heat demand		**Savings**	**Total**	**Heat Pumps**	**Heat nets**
	TWh heat		TWh heat	TWh heat	TWh heat
Households	88	25%	66	56	10
Utilities	39	25%	29	24	4
Industry	16	25%	12	11	2
Agriculture	26	25%	20	19	4
Others	6	25%	3		
			+----	+----	
Total LTH demand:	**175 TWh**		**130 TWh**	**110 TWh**	**20 TWh**
An overall LT heat demand saving of: 45 TWh (25%)					

Table 6 LT heat demand 2050 compared with the current (2015) demand

3.3.3 High-temperature heat demand and feedstock demand 2050

The high-temperature (HT heat) demand fully originates from the industrial sector, in particular from the process industry. The current HT heat demands for the various sub-sectors are listed in Table 4.

For energy savings and deep decarbonizing, we follow the analysis of CE Delft 2017 (ref. 11):

- Improving or even completely replacing current production processes and product design based on material circularity and recycling.
- Replacing the fossil fuel-based heating system by electrical and hydrogen furnaces.
- Processes with heat temperatures between 100 up to 250 °C can be equipped with industrial heat pumps with COP of 4 or better.
- Re-use of products and recycling of end-of-live products.

- For completely decarbonizing the sector only renewable electricity and hydrogen will be used as the energy carriers.

We expect for most (but not for all) of the industrial sectors an annual growth of about 1% in line with the EU/International based scenario of the Berenschot 2020 study. Voluminous parts of the Dutch industry like chemical and crude steel production, but also the agriculture section is strongly exporting sectors and we assume that this will be about the same situation in 2050.
Looking to the various sub-sectors, the energy and feedstock demands will be decarbonized in the following way.

Basic steel production

The current 7.5 Mton steel production is with 12 Mton CO_2 emission a major source in the total greenhouse gas emission (ref. 12). By replacing the cokes with green hydrogen as the reduction medium in a direct reduction process (ref. 13 - 14) the CO_2 emission will be reduced to almost zero. The iron scrap recycling will grow from the current 25% to 50% in 2050. The production of crude steel will hardly grow coming years and the 2050 production will be assumed to be about equal with the current (2015) production of 7.5 Mton steel. A prominent example of a sustainable iron production process is the Swedish Hybrit process with 3 basic process steps in the Hybrit crude steel making being (see also ref 14):

- The iron pellet plant production of clean iron ore pellets from the crude iron ore in the pellets iron ore plant. This production process asks some energy (green gas). This will be produced from biomass.
- Reduction of the iron ore to basic iron using hydrogen as the reduction medium. The process type use is direct reduction of the iron ore, called direct reduction iron (DRI). Typical process temperature is 800 °C , producing so called sponge iron.
- The sponge iron complimented with iron scrap is melted down to crude steel in an electric arc furnace. This electric arc melting process asks 5 TWh per Mton output of crude steel. A bit CO_2 will be emitted with this process.

Based on this Swedish Hybrit (ref. 14) crude steel process the 2050 Dutch steel production of 7.5 Mton crude steel will ask 11 TWh hydrogen plus 37.5 TWh electricity, as calculated in appendix B. CO_2 emission is no more than 7.5 x 25 = 188 Kton CO_2.

Ammonia production

Current ammonia production is 2.5 Mton, mainly used in the fertilizer industry and for a minor part in the plastic industry. The ammonia may be considered as a feedstock. The production process is based on synthesizing air nitride with hydrogen based on the well-known Haber-Bosch process asking a high temperature and pressure. The hydrogen is now produced by reforming natural gas, a process responsible for strong greenhouse gas emission. Decarbonising the process will be done by producing the hydrogen through electrolysis with green electricity, resulting in green hydrogen and leading to significant energy saving (Berenschot ref. 5). The ammonia demand in 2050 will be also significantly lower due to the EU-wide approach to a strongly circular agriculture, which will lead to a reduced Dutch ammonia demand with 40% reduction in line with the CE-Delft 2017 study (ref. 11). Total production is reduced to 1.5 Mton ammonia. With the efficient green hydrogen production only 10 TWh = 0.25 Mton (higher heat value, HHV) hydrogen will be necessary.

Plastic industry

In the road map to a fully sustainable plastic industry, the sector will concentrate on improving current processes or replacing with completely new processes resulting in:

- re-use and maximal recycling properties of the plastic products;
- improved heating systems using electricity and hydrogen based heating systems, resulting in much lower heating demand.

Dutch targets for the own Dutch market in the coming decades are: the plastic pact 2025 aiming to 35% recycling for the packaging industry with 70% high-value applications, 2030 targets with a reduced fossil share of 60% and a 40% share with recycling and biomass-based production. The ultimate ambition is no fossil fuels, no primary feedstock but a 100% circular economy (ref. 15)
Due to this a significant energy saving will result! But on the other hand, there will be still some economic growth of about 1% coming years and including the extra heat required for the conversion of biomass to the new basic commodities for the plastic industry, the 2050 heat demand will be assumed to be about equal to the current demand.
The feedstock is based on woody biomass as a good source for carbon (ref 10), with a recycling part, which will grow to 50% in 2050, for the total production domestic and export production included.

Feedstock demand 2050 for the plastic industry

Current (2015) feedstock demand is 114 TWh fossil naphtha (= 9 Mton using the specific energy of 12.5 kWh per kg naphtha). The naphtha is converted to C_2-C_4 olefins, the basic building blocks for the plastic industry, with ethylene (C_2H_4) is the most prominent one. Most of the plastics produced from the olefins are exported. Only 20% of the production is for the domestic market (NVCI, ref. 16). As an average annular growth of 1% is assumed, the feedstock has also to grow with this same rate, meaning that the required feedstock will grow to 150 TWh in 2050.
Wood from sustainable forestry will be used as green feedstock.
Recycling the end-of-live plastic products will play an important role in the chemical industry of 2050, an expected 50% of the plastic products will be recycled to new products. With a 50% recycling level,75 TWh feedstock will be delivered by end-of-live plastics. And as a result of that half of the required biomass feedstock is necessary, meaning that 75 TWh fossil naphtha (=6 Mton) has to be replaced by woody biomass.
Converting biomass to the olefins, indicated as bio-refinery, is a complex process (ref. 10). Most of the current sustainable processes are based on fermentation of biomass types as cane sucker and corn is used. The advantage of this process is that no high-temperature heat is required. But this conflicts with the constraint not to use biomass meant for the food sector. Therefore, wood should be an better choice and is of course a perfect carbon source: the average composition of wood is 50 wt% carbon, 6 wt% hydrogen, 44 wt% oxygen plus some minor elements as nitrogen, sulphur, chloride etc.(ref. 10a).
Core question in our study is the required wood mass for the conversion of wood to the olefins.
Among other process routes for the conversion of wood to olefin, the major process approach is a 3 steps process line (ref. 10b):

- The first step is gasification of the wood to producing syngas, a mix of hydrogen and carbon monoxide from the wood. With optimal catalytic approach the conversion efficiency from wood gasification (in a 2-step process) is a factor 0.7 (ref 10c)
- The next step will be the conversion of the syngas to methanol, ethanol. Efficiency of this process step is about 0.6 (ref. 10d)
- The final, third step is the conversion of the methanol, ethanol to ethylene and other olefins. This process has an efficiency of 0.5 (ref 10e)

The resulting overall conversion efficiency from this process line is therefore 0.2 or the production of 1 ton ethylene asks 5 ton wood.
The conclusion is that the required wood feedstock, replacing the 6 Mton fossil naphtha, 30 Mton (= 150 TWh) wood will be necessary for a sustainable 2050 plastic industry.

Availability of the required biomass

A source for the required biomass is rest wood from the forestry and the waste and end of live products from the Dutch wood industry.
From the PBL study on biomass, 2020 (ref. 26), it appears that 22 TWh=4.5 Mton biomass is produced by forestry: production plus rest streams. Wood Import is 5.5 Mton (ref. 27). This means that 10 Mton wood is used in the Dutch forestry and wood industry. So, for the basic feedstock for the chemical industry the rest stream, waste and end of live products from this 10 Mton wood are available. As 30 Mton wood as biomass is required, it is clear, that most of the biomass feedstock has to be imported.
A warning on the possible availability of the required imported biomass is necessary. According to their study on biomass PBL estimates the import of biomass in 2050 between 30 TWh and 210 TWh. The required 150 TWh biomass - if necessary to be imported - is within these limits. But reducing the required biomass by improving the conversion of biomass to effective feedstock as pyrolysis oil should be an important drive. Also increasing the share of end-of-live plastics as feedstock, more than the assumed 50% is of great importance.

The role of recycling end-of-live plastic

Mechanically based recycling plays an important role for recycling the thermo softening plastics. Good separation of the plastic waste is important, new separation methods as sensor-based separation will be used.
For thermosetting plastic with irreversibly hardening, chemical recycling will be necessary. Especially the reinforced plastics with glass or carbon fibre will be recycled in this way. An import example will be the recycling of the wind turbines blades. Pyrolysis will be the most common technology of chemical recycling between some other technologies. This pyrolysis will result in so called pyrolysis oil what will serve as new feedstock. See for instance the British recycling company Itero (ref. 24) with advanced and efficient new recycling processes based on pyrolysis. Also, the MsC study “Recycling wind turbine blades”, Julia Koelega, TU-Delft (ref. 25) on recycling end-of-live wind turbine blades gives a good analysis of the pyrolysis technology for the recycling of this type of carbon fibre reinforced plastic products.

E-Refinery as alternative for the bio refinery

For the bio refinery the starting point is the production of syngas from wood via gasification as mentioned above. This syngas can also be produced with direct electrolysis of water and CO_2. The high-temperature solid oxide type electrolysis applying co- electrolysis of both H_2O

and CO_2, is an attractive option for that. The processing of the syngas to olefins consists of the same steps as mentioned above.
This so-called e-refinery is an important study subject of TNO-Voltachem (ref.7). The Wuppertal Institute supports the study with the modelling and calculations. The major results for the production of ethylene via e-refinery are: the production of 1 ton ethylene requires 27 MWh green electricity and 3.1 ton of CO_2 (ref. 8).
So, the 2050 total demand of 6 Mton ethylene (as stated above) requires 18 Mton CO_2 and the production of 162 TWh electricity. If this electricity should be produced with wind parks on the North See, in total 36 GW wind on see will be required. For all other electricity demand 60 GW wind on see is already reserved in the EnergyNL2050 plan, being close to the maximum capacity which can be expected from the Dutch EEZ. This means that much of the 162 TWh electricity may be imported in this e-refinery approach.

Refinery industry

As road transport and all shipping are based on fully electrical propulsion (battery based or hydrogen fuel cell based), the refinery for transport fuels has almost completely disappeared. Only aviation transport needs still kerosene. For the summary see table 7.

The HT heat demand 2050 plus feedstock is summarized in the next table:

	2015	**2050**	
	Thermal + non-thermal	**Thermal + non-thermal**	
	Fossil	**green H2**	**Electricity**
	TWh	TWh H2	TWh el.
. Basic steel	29	8	5.5
. Ammonia industry:	26	10.5	
. Chemical industry	55 *(+114 TWH non-Thermal)*	27.5	27.5
. Refinery energy	50	-	-
. all others	25		27
	+----	+----	+----
Total 2015 HTH demand:	**185 TWh**	**46 TWh H2**	**60 TWh el.**
2015 Feedstock demand for the chemical industry: 114 TWh (naphtha)		**2050 feedstock demand: 75 TWh end-of-live plastic +150 TWh wood**	

Table 7 HT heat demands plus feedstock demand 2050 compared with de 2015 demands

3.3.4 Transport energy demand 2050

Current fuel demand in the transport sector is almost fully fossil based. And beside this the propulsion engines are of the combustion type. Resulting in bad efficiency properties. As an example, the average tank to wheel efficiency of a personal car is only 25%. An electrical propulsion motor has an efficiency of 90% and the tank to wheel efficiency is 75% for a battery-based propulsion.

Due to both facts the current greenhouse gas emission is with 40% a significant part of the total annual CO_2 emission.
To fully decarbonize this sector, it will completely be based on electrical propulsion and with green electricity or green hydrogen as the only energy carriers. Not only for road transport but also for the shipping sector.
Some transport demand growth is expected coming years due to the economic growth. But energy demand will grow hardly anyway. Road use and transport management will continuously be improved by new real time data-based information systems. And despite the economic growth the fuel demand will be still about the same as the current one.
Estimating the 2050 demand for electricity and hydrogen can be performed using the tank to wheel ratio for both propulsion systems: combustion engine and electrical motor system.
The results for that are summarized in the next table:

	2015	**2050**	
	Fossil based	**electricity**	**hydrogen**
Transport type	TWh	TWh	TWh
Passenger cars:	74	25.5	
Lighter road transport:	15	5	
Heavy road transport:	22		16
Other road transport	10		7
Fishing and domestic shipping:	30		22
Inland aviation: 0.25 Mton kerosene	3	*2.5*	*1*
	+----	+-----	+----
Total energy demand Transport	154 TWh	33 TWh	46 TWh

. For compression of the hydrogen an additional 5 TWh electricity is necessary.
. The 2050 domestic aviation requires 3 TWh kerosene. Production requires 2,5 TWh electricity plus 1 TWh hydrogen.

Table 8 The 2050 transport energy compared with the current demand

The 2050 transport energy demand will be reduced from 154 TWh fossil fuels down to 78 TWh (33 TWh green electricity and 45 TWh green hydrogen).

3.3.5 Fuel demand for international aviation and shipping

As already explained in the 2020 paper international energy accounting rules are such that the fuel for the international shipping and aviation will not be taken with the total energy demand, the associated greenhouse gas emissions are also not included within the Dutch CO_2 emission. But this fossil fuel demand needs still to be decarbonized.
Summary of the results based on the 2020 paper:

- The propulsion systems of the international shipping sector will be fully replaced by electric propulsion systems based on liquid hydrogen (or methanol as an alternative) fuelling fuel cells. Assuming the same fuel demand in 2050, equal to the current demand of 12.3 Mton diesel (= 145 TWh), due to the better efficiency of the full electric propulsion the liquid hydrogen demand 2050 for the international shipping sector is 100 TWh (= 2.5 Mton) liquid hydrogen.

- As is assumed that the 2050 aviation sector still uses kerosene, the current fossil based kerosene (3.7 Mton = 48 TWh) will be replaced by synthetically produced kerosene from syngas (mix of hydrogen and carbon monoxide). Assuming the same kerosene demand 2050, the required hydrogen for the kerosene production will be about the same size: 48 TWh hydrogen.

Both international transport sectors fuelled from the Dutch bunkers will ask in 2050 116+42=3.8 TWh (4 Mton) green hydrogen. For the domestic final energy demand - with 92 TWh hydrogen in the demand mix - has been already reserved 60 GW offshore wind energy, being fairly close to the upper limit for offshore wind in the Dutch EEZ of the North see. It is clear from this, the 3.8 Mton hydrogen for international shipping and aviation must be imported.

3.3.6 The transport and temporary storage of the produced hydrogen.

The hydrogen produced by the electrolysis plants has to be transported to the users: industry, road transport, hydrogen fuel-cell based backup systems. We expect that the major transport carrier will be a hydrogen gas net, being also part of an EU wide hydrogen gas net. The hydrogen gas net is equipped with gas pump systems using electricity. This electricity is part of the basic electricity demand 2015 and also in the case of the 2050 demand. The gas net will also have some gas leakage. In the 2018 paper on our study we estimated this hydrogen leak to be about a high 10% and in the 2020 paper still a high 8.5% loss. But we now realize, this leak is much too high: we may expect that the leakage will be lower than 1%, and for safety reasons it should be even lower.

Therefore, we refine the leak losses in the hydrogen transport and temporary storage to be lower than 1%.

3.4 Summarizing the total refined energy demand in 2050

Energy demand per function	2015 Fossil based	2050 Renewable based Electricity	 Hydrogen	 Heat nets
	TWh	TWh el	TWh H2	TWh heat
Basic electricity	104	110		
LT Heat demand	175	29	-	20
HT heat demand	185	60	46	
Transport	154	33	46	
H2 compression (200-700 Bar)	-	5		
	+----	+----	+----	+----
Total energy demand:	618 TWh	237 TWh el.	92 TWh H2	20 TWh heat

Total demand 2050: 349 TWh
Also heat from: outside air/groundwater/surface water for the heat pumps: 110 TWh heat for LT heat demand
The 20 TWh heat nets require a gross 25 TWh heat from the rest heat of the electrolysers and back power plants.
The 2050 feedstock for the chemical industry is 150 TWh: 75 TWh end-of-live plastic will be recycled. Biomass will be used to deliver the additional required feedstock, requiring 150 TWh biomass.

Table 9 Final refined energy demand 2050 compared with the current (2015) energy demand

3.5 Major conclusion

Already noted in the 2020 paper, but important to repeat: what are the major adaptations for a green energy system:

- ***Use heat pumps for producing the low temperature heat taking advantage of the coefficient of performance up to a value of 4 or higher.***
- ***Industrial product design based on re-usability and recyclability.***
- ***Full transfer to electrical propulsion systems in the transport sector (road and shipping as well), battery based and hydrogen fuel cell based.*** This reduces the functional energy demand 2050 to about half of current one.

4 The EnergyNL2050 system refinement of renewable energy sources in 2050.

The mix of the renewable energy sources are discussed in our 2020 paper on the EnergyNL2050 plan, mainly based on electricity from wind and solar power. We may also expect still some contribution from new renewable sources. Now still in the research phase, but with the potential to develop to mature cost-effective energy sources.

4.1 Possible other renewable sources beside wind and solar power.

Promising sources are from marine based energy sources as wave and tidal energy. Another promising source is so called "Blue Energy", a technology which yield electricity, when fresh water from a river and salt seawater are mixed in stacks with cation/anion selective separation filters. As Netherlands is a delta of the rivers Rhine and Meuse, the potential of blue energy is significant. The company REDstack has installed a blue energy 50 KW pilotplant on the Afsluitdijk, using the freshwater from the IJsselmeer and the salt water from the Waddensea (ref. 17). Annual electricity production is 400 MWh with 8000 full load hours. REDstack estimates that blue energy has a potential of 750 MW/6 TWh in the Netherlands. CE Delft estimates in a 2020 study on "perspectives on electricity from water" ref. 18) a potential of 8 TWh per year from tidal and wave energy plus the blue energy potential. Tidal energy potential can strongly grow, using a system of 3 long walls perpendicular to the Dutch coast in the North Sea, with specially chosen distances between the walls. In the walls the tidal electro generators are mounted. With this so called "dynamic tidal power" (TDP) approach with wall length of 30-50 km up to 20-60 TWh/2000 full load hours electric energy could be generated. Together with the wave energy and blue energy at least 20 TWh as "other renewables seems possible. But this DTP system is still in a study phase, it will be clear that DTP is quite unclear if it could be realized. For this reason "other renewables" from water electricity will be limited to the realistic 8 TWh electricity.

4.2 Resulting mix of renewable energy sources:

As a result of the above explanation, the mix of the renewable energy sources is as follows (see table next page, and also see the high level energy system diagram of appendix A).

Other main results, based on the simulation results and clearly discussed in the 2020 paper:

- Curtailment: 6 TWh/yr
- One Day Storage system (battery based, decentralized) capacity: 80 GWh
- Electrolysis system producing the required hydrogen: 40 GW, 3600 full load hours
- Fuel Cell Backup System: 16 TWh/yr, 35 GW, 485 full load hours

Renewable Energy Sources	Power GW	Energy/year TWh.el	Contribution %	full load hours
1. PV	78	72	18	920
2. Wind offshore	60	272	67	4500
3. Wind onshore	6	14	3.5	2500
4. Other renewables	1	8	2	8000
5. Import electricity	5	40	9.5	4000
6. Import hydrogen		--	--	
		+-------		
Total primary energy demand		406 TWh electricity.		

Table 10 The mix of renewable energy sources for the energyNL2050 system ("Other renewables" means energy sources we may expect coming decades, but yet in pilot phase)

4.3 The required hydrogen buffer size for stable and reliable operation.

Securing a stable and reliable electricity and hydrogen system in 2050 comparable with current requirements, requires a minimal hydrogen buffer. This is already explained in the 2020 paper (ref. 3), but looking to the importance of this subject, shortly summarized with a little improvement based on own calculation with the new refinement results .

. The seasonal variations in wind- and PV electricity -surplus in the winter and deficit in the summer due to ratio wind/PV electricity = 4 on an annual base, requires a buffer size of 12 TWh hydrogen(= 0.29 Mton H_2.).

. A long 4 weeks dunkelflaute with almost no production of wind- and PV electricity. A dunkelflaute of about 10 days with almost no wind- and PV electricity requires 12 TWh hydrogen from the buffer, as can be seen in figure 2, showing the buffer development during the simulations in the first weeks of January 2017. So a long 4 weeks dunkelflaute requires a buffer of rounded 30 TWh hydrogen (= 0,76 Mton H_2).

Both seasonal and 4 weeks dunkelflaute together requires a buffer size of 42 TWh hydrogen (=1.1 Mton hydrogen), 8 TWh lower than the 50 TWh as claimed in the 2020 paper.

. A bad year with seriously less wind and solar supply also means an available long term hydrogen storage. Such less annual sRE production can be down to 10 % of a long-term average year. This means a potential, annual deficit of 36 TWh hydrogen (see the wind- and PV-electricity parts in table 4.1), which may be compensated with a long-term hydrogen buffer of 36 TWh. But a possible alternative may be importing required additional hydrogen, when necessary, in a bad year.

From TNO studies (see "Underground storage in the Netherlands", S.F. van Gessel TNO et al, 2018, ref. 35) those numbers for the required buffer size are well possible in depleted offshore natural gas fields, the combined occurrence of those 3 situations will be very scarce. A 36 TWh hydrogen buffer for seasonal and 4 weeks dunkelflaute will be usable based on the new refined outcomes.

The system simulations, fully explained in the 2020-paper, show the development of the hydrogen buffer in the simulation years 2016, 2017 and 2018 in the appendix C, fig C.3.1. and is also shown in the next figure 4.1

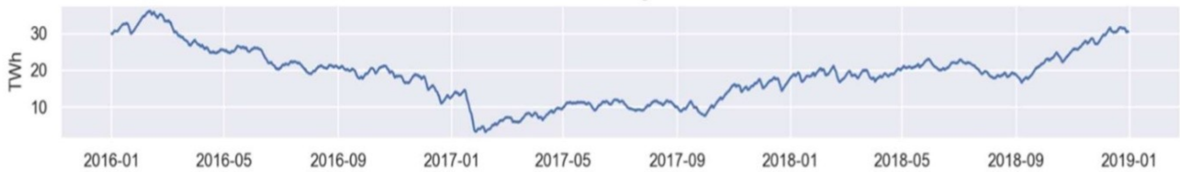


Fig. C.3.1 Time Series of the One Day Storage and Hydrogen Backup System for NL2050

Figure 2. Hydrogen buffer development during the simulation period 2016-2018.

It can be clearly concluded from the graphic that the 2016 year starts with some filling the hydrogen buffer up to 40 TWh. But continuous emptying during the year down to 10 TWh at the end of the year, indicates that 2016 is a year with less produced electricity from wind and solar compared with an average year.
A 10 days long dunkelflaute beginning 2017 asks 12 TWh from the buffer. But that year and 2018 produces enough surplus to fill the buffer to a good level. Required buffer size has to be 40 TWh hydrogen in this simulation.

5 Discussion on the refinements of demand and resources in 2050

5.1 Final energy demand results compared

The results for the demand have been discussed in chapter 3. For easy comparison, the current conclusions of (page 20) have been copied below, as well as the results from the 2020 paper (table 2.1 of chapter 2).

	2015	**2050 Renewable based**		
Energy demand per function	**Fossil based**	**Electricity**	**Hydrogen**	**Heat nets**
	TWh	TWh el	TWh H2	TWh heat
Basic electricity	104	110		
LT Heat demand	175	29	-	20
HT heat demand	185	60	46	
Transport	154	33	46	
H2 compression (200-700 Bar)	-	5		
	+----	+----	+----	+----
Total energy demand:	618 TWh	237 TWh el.	92 TWh H2	20 TWh heat

Total demand 2050: 349 TWh

Also heat from: outside air/groundwater/surface water for the heat pumps: 110 TWh heat for LT heat demand

The 20 TWh heat nets require a gross 25 TWh heat from the rest heat of the electrolysers and backup power plants.

The 2050 feedstock for the chemical industry is 150 TWh. 75 TWh end-of-live plastic will be recycled. Biomass will be used to deliver the additional required feedstock, requiring 150 TWh biomass.

Table 11 The refined final energy demand 2050 compared with the current (2015) energy demand (copy of Table 9, page 19). The refined final demand is 349 TWh.

Functional Energy Demand	2015 Fossil based TWh	Electricity TWh	2050 Hydrogen TWh	Heat Nets TWh
Basic electricity demand	120	127		
Transport	160	28	47	
Hydrogen compression (700 bar)		5		
High Temperature Heat	160	26	60	
Low Temperature Heat	200	25		20
Total Demand TWh	**640**	**211**	**107**	**20**

Table 12 Functional energy demands 2050 compared with the 2015 demands in 2020 paper. The 2050 final demand is 338 TWh

5.2 The energy demand in 2050

Summarizing the detailed analysis of the previous chapters, these are the main differences for the 2050 demand:

- Total 2015 demand: the refined value of 618 TWh is 22 TWh lower due to the new results from our CBS energy balance analysis (Appendix C). The change is relatively small.
- LT heat demand in 2015 lower by 25 TWh because of the refined analysis. Partly shifted to HT demand.
- HT heat and the feedstock demand
  The 2015 starting value in this refined 2022 paper is 185 TWh, 15 TWh more than in the 2020 paper (ref. 3). The 2050 value has been better analyzed using the approaches of this study. Due to this the higher electricity demand of 60 TWh and the lower hydrogen demand of 46 TWh resulted.
- Transport
  For the analysis of the expected transport energy 2050 we have the same approach of our 2020 paper (ref. 3): the 2050 amount will be about the same as the 2015 demand and the propulsion systems are fully switched to electric drive systems: battery based, or hydrogen fuel cell based. Only air transport is still based on combustion propulsion with green kerosene. The light road transport was in our 2020 paper fuelled with hydrogen plus fuel cells. But we assume that this lighter road transport will mostly use battery based electric propulsion, so this option is introduced in this 2022 paper.
  The new analysis is much more detailed, leading to different efficiencies for the various transport sectors. Due to that somewhat higher electricity of 33 TWh resulted plus a slightly lower hydrogen demand of 46 TWh.
- Hydrogen transport and temporary storage systems. The hydrogen gas leak is lowered from more than 5% to lower than 1%.

The overall energy demand changes only little: in 2020 paper it is 338 TWh, while we now estimate 349 TWh in 2050 (an increase of 3%). The hydrogen needs decrease from 107 to 91 TWh and the electricity needs increase from 211 to 237 TWh.

5.3 Renewable energy resources, results compared

Renewable energy resources have been discussed in chapter 4. For easy comparison, we copied Table 10 (page 22) below, as well as the results of the analysis in the 2020 paper (Chapter 2 table 2.2).
The main difference is the fact that PV and wind both increased (4% PV and 3.5% wind offshore) to accommodate the different type of demand and the decrease of other renewables, from the more optimistic 20 TWh to the realistic 8 TWh.

Renewable Energy Sources	Power GW	Energy/year TWh.el	Contribution %	full load hours
7. PV	78	72	18	920
8. Wind offshore	60	272	67	4500
9. Wind onshore	6	14	3.5	2500
10. Other renewables	1	8	2	8000
11. Import electricity	5	40	9.5	4000
12. Import hydrogen	--		--	
		+-------		
Total primary energy demand		406 TWh electricity.		

Table 13 The mix of renewable energy sources for the energyNL2050 system (2021 paper) (copy of Table 10, page 22)

Renewable Energy Sources Mix	Power GW	Energy/year TWh.el	Contribution %	full load hours
1. PV	77	71	17%	920
2. Wind offshore	60	269	65%	4500
3. Wind onshore	6	14	3%	2500
4. Other renawables	2,5	20	5%	8000
5. Import electricity	(variable)	40	10%	
6. Import hydrogen		-		
Total Primary Energy Demand		414	TWh	

Table 14 The mix of renewable energy sources for the energyNL2050 system (2020 paper (ref. 3). “Other renewables” mean energy sources we may expect coming decades, but in research phase

6 Consequences for the system verification and implementation

In the 2020 paper (ref. 3) system verification, the financial analysis and implementation aspects have been described extensively. The previous results show a slight change in energy mix and the amount of energy used in 2050. These numbers have been verified by using the time series model of the EnergyNL2050 system. The results are already included in the refined numbers.

6.1 Verification and financial analysis

As is clear from the data in the previous chapter, the changes are minor. Therefore, a more detailed analysis was not carried out. For the result of the dynamic characteristics of the EnergyNL2050 system and the financial analysis we refer to the results in the 2020 paper (ref. 3) chapter 3 and 4.

6.2 Implementation aspects.

In the 2020 paper the set-up of the total Dutch energy system is discussed. The refined demand and resource data do not change the basic considerations and results. The progress to be made in providing the resources is still huge. The increase in resource needs will make it even more difficult, but not much. There is still a strong need for managing peak powers and providing the proper infrastructure. For the results we refer to the 2020 paper chapter 5 (ref. 3).

7 Alternative design options for the energy system in The Netherlands

The energy system described in this paper generates more than 85% of the nationally needed energy (solely with renewable sources) and needs at most 15% import from abroad. Furthermore, the design optimises the ratio between solar and wind production capacity to minimise the amount of seasonal energy storage required. Finally, we strive for minimum energy demand in the build environment with all-electric heat pumps and heat nets.
In this chapter we outline alternative designs that could be the subject of further study.

7.1 Alternative A: increased use of imported hydrogen

Currently The Netherlands exports a large amount of petroleum-based energy carriers. While in 2050 some of this will be replaced by alternatives still demand will remain for synthetic kerosene and feedstock for the plastics industry. It has been decided to facilitate this by developing a hydrogen infrastructure across Europe, resulting in the potential availability of hydrogen at attractive price points. An alternative system design can be envisaged where:

a. the amount of locally produced hydrogen is reduced with a corresponding reduction in required generating capacity and possibly a larger fraction of solar energy versus wind.
b. there is an increased role for hydrogen in the built environment. Especially for dwellings built in the last quarter of the last century the use of hybrid heat pump with hydrogen-based furnaces as a back-up is financially attractive and reduces the need for network capacity and electric backup generation increases.

An initial analysis indicated that this could lead to reduction of the overall energy system cost and perhaps more importantly to a simplified transition in the build environment and reduced need for network expansion.

7.2 Alternative B: nuclear energy

In our system design we have excluded the use of nuclear energy for three reasons: the uncertainty about long term storage of nuclear waste; the long and uncertain lead-times; the high investment costs. Our analysis demonstrates that nuclear energy is not required for a reliable energy system. As a back-up system, nuclear power plants are even less attractive since they will operate only incidentally. In the proposed concept, the cost of the energy back-up infrastructure is a modest fraction of the total system cost.

8 Conclusions

The main objective of this paper is to supplement our 2020 paper (ref. 3) with detailed and new background information regarding our estimation of 2050 energy demands: what will be the future demands and in what way could the demands transfer to green hydrogen and electricity.

The in-depth study of the CBS energy balance for our starting year 2015 improved our starting point with a better-defined energy demand estimate in 2015. It also improved the insight in the energy usage.

Inputs from more recent studies – CE Delft 2017 study on “the electricity grid of the future” (ref. 11) and the Berenschot 2020 study on “climate neutral energy scenario’s” (ref. 5) – gave good inputs for comparing our results in the 2020 paper (ref. 3) with newer insights.

Recycling will play an important role reducing future energy feedstock demand. Refinement of the resulting functional energy and feedstock demand could lead to a shift from less hydrogen demand to more electricity demand. We have not quantified this possible shift.

The mix of renewable energy demand was also adapted to the new knowledge. The future new sources were expected to contribute with 20 TWh electricity. But this estimation was too optimistic; a more realistic value is 8 TWh. The new primary energy demand is slightly lower (406 TWh instead of 414 TWh).

9 Acknowledgment

We thank our reviewers for their useful comments and suggestions. Especially the comments by members of “Klankbordgroep Ingenieurs en Energietransitie” from KIVI. We thank Richard Overkamp and Jan Vleeshouwers for reviewing this document.

10 References

1. EnergyNL2050” the results of our study on a full carbon free Dutch energy system 2050, E. Persoon et. al 2018 from KIVI Electrical Engineering website
2. Richting 2050: systeemkeuzes en afhankelijkheden in de energietransitie. B. den Ouden et. al, Berenschot May 2018.
3. Design of a Dutch carbon free energy system, energyNL2050, E. Persoon et al., 2020 from KIVI Electrical Engineering website (indicated with “the 2020 paper”)
4. Verkenning functionele energie vraag 2015. CE-Delft, Warringa, F. Rooijers, 2015
5. Klimaat neutrale energie scenario’s 2050. Berenschot, 2020
6. MAN energy solutions for info on industrial heat pumps. Site: www.man-es.com
7. Deep decarbonisation of the Dutch heavy industry through electrification of the production of basic materials and transportation. T. van Harmelen, TNO/Voltachem 2020.
8. Decarbonising the energy intensive basic materials industry through electrification, 2017 Wuppertal university.
9. Pyrolyse olie, BEON 2021, www.stichtingbeon.nl/bio-energie/pyrolyse-olie/
10. Olefins from biomass intermediates, an overview. 2017, V.Zacharopoulou et al University Thessaloniki.

10a The chemical composition of wood. R.C. Pettersen, Department of Agriculture, Forest service.

10b LCA of biomass-based ethylene production in Sweden. Ch. Liptow et al.

10c Two-stage gasification of biomass for the production of syngas. R. Berends et al, TNO

10d Catalytic conversion of syngas to ethanol and higher alcohols over Rh and Cu based catalysts. L. Nina, Institute of Technology, Stockholm 2017, Thesis.

10e Ethanol to ethylene conversion. H. Poppick et al. 2015, USA.

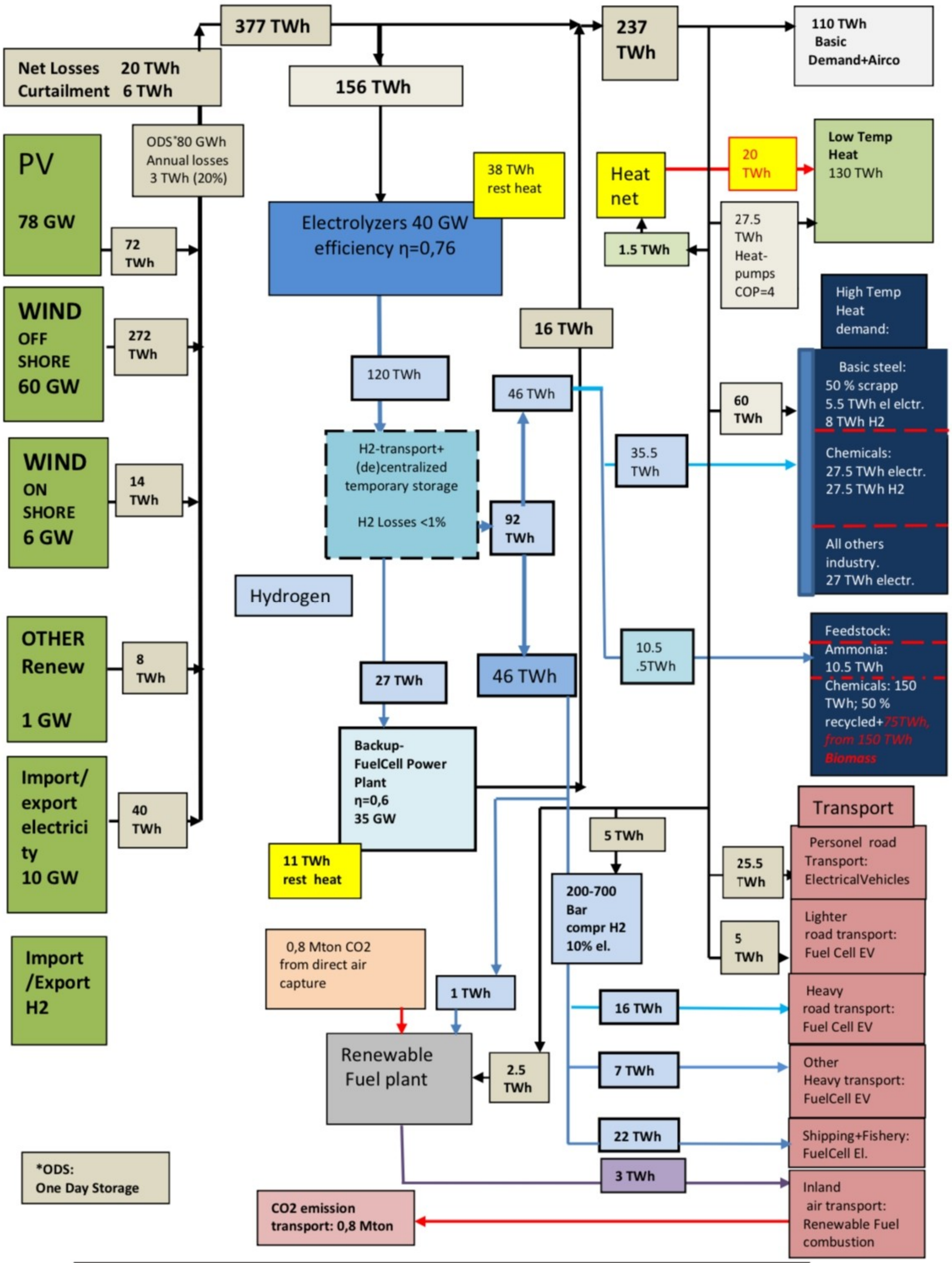
11. Net voor de Toekomst achtergrondrapport. CE-Delft M. Afman, F. Rooijers, 2017
12. CO_2-reductie in de staal industrie. Tata Steel, H Kiesewetter 2016. EnergyNL2050 presentation
13. Treibhausgasneutrales Deutschland 2050. Umwelbundesamt, 2014.
14. Hybrit fossil-free steel by SSAB, LKAB and Vattenfall. Site: www.hybritdevelopment.se
15. De circulaire economie van kunststof: van grondstoffen tot afval. A. Verrips, PBL, 2017
16. Chemistry for climate: VNCI roadmap to chemistry 2050. Berenschot, Ecofys 2018
17. Redstack information. Site www.redstack.nl
18. Perspectieven elektriciteit uit water, CE Delft & Witteveen+Bos, E. van Druten, K. Kruit 2019.
19. Bepaling energiebesparing door isolatie van woningen in de start analyse. R v.d. Wijngaart PBL 2020
20. Start analyse aardgasvrije buurten (conceptversie), S. van Polen at al, PBL 2020
21. White paper “Meer duurzame warmte door seizoensopslag” R Bianchi, Berenschot 2020

22. Monitoring heat demand, M. Menkveld et all, ECN/CBS, 2017
23. Info on Electro Thermal Energy Storage. Site: www.etes.com
24. Info from Itero, UK. Site: www.itero-tech.com
25. Recycling windturbine blades, J Koelega, 2019, TU-Delft
26. Beschikbaarheid en toepassingsmogelijkheden van duurzame biomassa. PBL 2020 B. Strengers en H. Elzenga
27. Info from the VVNH, www.vvnh.nl, Dutch Wood Industry Community
28. De impact van het bijmengen van waterstof op het gas distributienet en de gebruiksapparatuur. E. Polman en anderen, KIWA, Netbeheer Nederland 2020
29. Jupyter is a non-profit, open-source project, to support interactive data science and scientific computing (www.jupyter.org) .
30. Python open-source programming language (www.python.org).
31. Pandas open-source data analysis and manipulation tool for Python (www.pandas.pydatra.org).
32. Opendata CBS statline info (https://opendata.cbs.nl/statline/#/CBS/en/dataset/84119eng
33. Het energieverbruik voor warmte afgeleid uit de Energiebalans, R Segers, CBS 2009.
34. Biomassa voor de circulaire economie, WUR, J van Groenestijn, 2019
35. Ondergrondse opslag in Nederland. S.F. van Gessel en anderen , TNO. 2018

Interesting reading:

- E-Fuels: towards a more sustainable future for truck transport, shipping and aviation. R.P Verbeek, TNO 2020
- Diesel-electric propulsion plants, a brief guideline. Man Industries.
- Study on Introduction of CO_2 free energy to Japan with liquid hydrogen, page 29, S Kamiya, Kawasaki, 2014
- Refuelling assessment of a zero-emission container corridor between China and US (California), Xiaoli Mao, ICCT 2020
- Carbon neutral aviation with current engine technology, R. Terwel , Kalavasta 2018
- Direct air capture, utilisation and storage, M Bulut, Vito, 2020

Appendix A: High level block diagram energyNL2050-refined



Appendix A: High level block diagram energyNL2050 refined.
Annual primary energy: 406 TWh; CO2 emission : 0 (0,8) Mton.
PV= 20% of vRE

Appendix B: Energy demand 2050, some additional notes.

1. Low Temperature Heat Demand (T <100 C)

1.1. Current LT heat demand

This is the heat demand for the households, utility sector, industry and agriculture and is listed in the next table:

Low temperature heat demand	**2015 TWh heat**
Households	88
Utilities	39
Industry	16
Agriculture	26
Others	6
	+----
Total	**175 TWh**

Table B1: Current (2015) low temperature heat demand

Decarbonizing the LT heat demand.
Natural gas is the major energy source nowadays for this heat demand. To decarbonize this demand heat pumps will be the major heat sources for the build environment. Also, the heat nets will grow, using the rest heat mainly from the hydrogen electrolysis plants and the hydrogen fuel cell backup power plants. But an important role will play the heat saving by improved insulation.
Regarding the houses there are now almost 8 million houses and we may expect an additional 1 million houses up to 2050. 10-20% (9-18 TWh) of the 88 TWh heat demand is for the hot water heat demand in houses and buildings. As buildings build from 2000 on will have good heat insulation, meaning an energy label A or better certification, total space heat demand is almost completely determined by the older houses and buildings. Saving on this heat demand means improved insulation.
Using results from the recent PBL 2020 study on natural gas free build environment (5). that with good insulation steps already good heat saving can be obtained, being also affordable for the owners. Overall energy label B or better will result, with an average heat saving of 30%. Assuming the heat demand for the hot water systems is about the same 2015 level, the effective heat saving in the build environment will be 25% (own calculation). This means for most of those older houses and buildings heat pumps can be used , even during more severe cold situations with air temperature down to -10 °C.
For the low temperature heat demands in the two subsectors Utility and Industry the same 25% heat saving may be applied.

The agriculture and especially the horticulture will strongly be influenced by the circular approach coming decennia. Due to that the heat demand will be strongly reduced with about 25% (whereas the light demand will strongly grow!) (3).
Due to this savings the LT heat demand 2050 will be reduced down to a net 130 TWh heat.
Heat nets will grow from the current 6.2 TWh heat delivery to 20 TWh heat in 2050. Perfect heat sources for the heat nets are the rest heat from the many hydrogen electrolysis plants and from the fuel cell backup systems. These heat sources with temperatures of 80-90 dgr C will contribute 51 TWh rest heat as can be seen in the block diagram of appendix A, meaning large enough for the heat nets demand.
Heat pumps will deliver the required 110 TWh heat, private heat pumps for the households and industrial heat pumps for the larger buildings. All heat pumps are assumed to have an annual average value of COP=4, resulting in an electricity demand of 27,5 TWh.

1.2. 2050 heat nets situation

The heat nets deliver 6.2 TWh heat to 300,000 connections in 2015. Most of the heat (19.6 PJ= 5.5 TWh) will be delivered by 17 larger city heat nets and 2,2 PJ=0.6 TWh by a number of smaller nets.
Next figure gives a listing of the larger heat nets:

	Totaal aantal aansluitingen [duizend aansluitingen]	Warmtelevering [PJ/jaar]	Warmtelverancier
Utrecht	52,8	2,9	Eneco
Rotterdam	53,1	3,4	Eneco & Nuon
B3-Hoek	0,1	2,1	Eneco
Den Haag	4,9	1,1	Eneco
Ypenburg	10,1	0,3	Eneco
Amsterdam Zuid- en Oost incl. Amstelveen	15,5	1,3	Nuon & Eneco
Amsterdam Noord- en West	10,0	0,6	Nuon
Almere	49,0	1,7	Nuon
Lelystad	4,8	0,2	Nuon
Leiden	8,3	0,7	Nuon
Arnhem, Duiven en Westervoort	13,9	0,6	Nuon
Amernet	32,5	2,7	Ennatuurlijk
Enschede	6,3	0,5	Ennatuurlijk
Helmond	6,4	0,2	Ennatuurlijk
Eindhoven	4,1	0,2	Ennatuurlijk
Alkmaar en Langedijk	4,6	0,2	HVC
Purmerend	25,9	0,8	Stadsverwarming Purmerend
Totaal	299	19,6	

Figure B1: heat nets listing (ref 22: Monitoring heat demand 2015, ECN/CBS)

The heat nets are widespread about the country. Major heat source for the nets is the residual heat from combined heat-power plants, but also heat plants with biomass as feedstock or waste materials are applied.

All nets have the ambition to grow coming decades. We expect a grow from the 6.1 TWh heat in 2015 to 20 TWh in 2050. We consider the residual heat from the H2-electrolysis plants and the fuel cell backup systems as important heat sources for the heat nets. From the block diagram of appendix A, we see that this residual heat is 50 TWh heat, sufficiently large for supplying the 20 TWh heat for the heat nets.
The heat nets will have an annual average efficiency of 80% (ref. 22), therefor the heat sources should supply a gross 25 TWh heat. The pumps for circulating the hot water through the heat nets asks 5% electricity (ref. 22), resulting in an extra electricity demand of 1.5 TWh.

2015			**2050**		
Low temperature heat demand		**Savings**	**Total**	**Heat Pumps**	**Heat nets**
	TWh heat		TWh heat	TWh heat	TWh heat
Households	88	25%	66	56	10
Utilities	39	25%	29	24	4
Industry	16	25%	12	11	2
Agriculture	26	25%	20	19	4
Others	6	25%	3		
	+----		+----	+----	+----
Total LT heat demand: 175 TWh			**130 TWh**	**110 TWh**	**20 TWh**
An overall LT heat demand saving of: 45 TWh (25%)					

Table B2: LT Heat Demand 2015-2050.

1.3. Summarizing the LT heat demand

The required net 130 TWh LT heat demand will be produced by:

- **110 TWh heat from heat pumps, COP=4 requiring 27,5 TWh electricity.** The 110 TWh heat will be delivered from outside air, surface water and ground water sources.
- **20 TWh heat via heat nets with 80% heat efficiency and 5% electricity required for the hot water circulation pumps:** gross heat demand is 25 TWh from hydrogen electrolysis systems and from the hydrogen fuel cell backup power plants., the circulation pumps ask 5% = 1.5 TWh electricity.

Total electricity demand will be: 27.5 + 1.5 = 29 TWh electricity.

1.4. Remark on heat from hydrogen electrolysis plants and backup systems

Although most of the heat nets will be able to use the rest heat from the electrolysis plants and backup systems, there will be still some heat nets too far from those heat sources. Other rest heat sources from local high temperature are scarce, and also waste materials as end of live plastic and wood for local heat plants are very scarce due to a strong circular economy. In such situations a good alternative is producing the heat with industrial heat pumps and using the relative heat from surface water, like lakes, canals etc. A good example for such industrial heat pumps is the heat pumps from the Swiss company MAN based on their electro thermal energy storage system (ETES), with coefficients of performance (COP) of 4 or higher (ref. 23, www.etes.com)!

2. High-Temperature Heat (temperatures >1000 C) plus feedstock demand.

2.1. The current HT heat demand (2015)

This high-temperature heat demand is entirely required for the industrial sector. In line with the 2020 Berenschot study on climate neutral energy scenario's (ref. 5), the current (2015) HT Energy demands are:

Fossil	**Total TWh**	**Thermal TWh**	**Non-Thermal TWh**
. Basic steel	29	11	18
. Ammonia:	26	7	19
. Chemical industry	55	55	*(114)*
. Refinery energy	50	34	16
. all others	25	25	
	+----		
Total 2015 HT heat demand:	185 TWh		

Fossil feedstock demand for chemical industry: 114 TWh (naphtha from the refinery sector)

Table B3: HT heat demand 2015.

2.2. 2050 HT heat and feedstock demand from the industry: steel production

Based on this Hybrit steel-making process, as mentioned in the main part section 2, the typical process figures are for the production of 1 ton liquid crude steel:

- for the making of clean iron ore pellets: 0.5 TWh biomass plus 0.039 MWh electricity to be used in the pellet plant,
- for production of 1 ton sponge iron with the direct reduction iron process: hydrogen: 2.1 MWh H2 (from the electrolysis plant asking 2.633 MWh electricity) plus 0.32 MWh electricity,
- 0.5 MWh for the electric arc furnace when the sponge iron and iron scrap are mixed to 1 ton crude iron. During this process step some minor coal is added, necessary for the required good mechanical properties. According to the Hybrit process, this will be 5.5 kg coal (= 0,042 MWh coal).

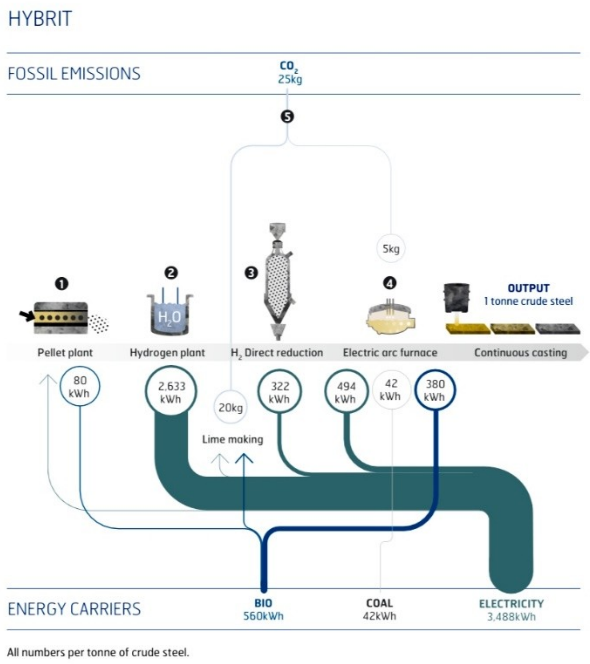


Figure B2 The Hybrit decarbonized steel making process compared with current blast furnace process. (Courtesy Hybrit, ref. 14)

The 2050 Dutch steel production of 7.5 Mton crude steel with 50% recycling, uses 3.75 Mton sponge iron plus 3,75 scrap. Using the above figures, this will ask 8 TWh hydrogen plus 5.5 TWh electricity. 21 kg Coal (= 0.150 MWh) will be added during the melting process. Also 2.1 TWh biomass will be used in the iron ore pellet plant.
CO_2 emission in all processing is not more than 7.5x25=188 Kton CO_2.

3. Transport

3.1. Current (2015) transport energy demand

74 TWh fuel energy for passenger cars and about 80 TWh for all other road transport plus fishing and domestic shipping. The energy required is almost entirely fossil based and the *tank-to-wheel efficiency* (TTW efficiency) of the various transport types differs between the different types.
In the next table the annual 2015 demand, the estimated TTW/TTProp efficiencies and the effective resulting energy delivered to the wheel axe resp. to the propeller axe for shipping are:

Transport type energy	TWh (fossil)	TTW/TTProp Efficiency %	wheel (propeller) TWh
. Passenger cars:	74	25	19
. lighter road transport:	15	25	3.8
. heavy road transport:	22	35	7.7
. other road transport	10	35	3.5
. Fishing and inland shipping:	30	40	12
. Inland aviation:	3 TWh kerosene (=0,25 Mton)		
	+-----		
Total transport energy demand 2015: 154 TWh			

Table B4: from the gross fossil fuel energy to the effective net energy at the wheel axes or propeller axes for the various transport types.

3.2. Transport energy demand 2050

Transport is fully switched over to electrical power propulsion systems, battery based for the passenger EV (BEV) plus light transport cars and hydrogen-fuel cell based for all other road transport (FCEV). Shipping has also been switched over to hydrogen – fuel cell based electrical power drive systems. Air transport only use green kerosene. The electrical drive systems have a much higher efficiency compared to the combustion systems nowadays:
From the effective net wheel /propeller energy in table B2.4 the gross renewable energy for the various transport can be calculated, using the efficiency results of the BEV and H2 fueled FCEV.
Economic growth is annually about 1%, but the annual energy savings may be assumed to be also about 1%. So, energy demand 2050 will be about the same energy as in 2015, more exactly a factor 1.05.

The passenger vehicles (BEV)

Efficiency of the battery system is 90%, the electrical motor system has an efficiency of 90% and adding mechanical losses of 5%, the tank-to-wheel (TTW) efficiency is 77%, meaning that BEV requires 25.5 TWh electricity.

Lighter road transport: also, fully battery based EV.

TW efficiency is also 77%, resulting in the required electricity of 5 TWh.

Heavy road transport: hydrogen fuel cell-based EV

The TTW-efficiency is lower than BEV due to the on-board fuel cell with 60% efficiency, but a large battery is not required in the direct propulsion line. So together with the 90% efficiency of the electro-motor system plus the 5% mechanical losses, overall TTW efficiency is 51%
So heavy transport requires 16 THW H_2.

Other road transport: hydrogen fuel cell-based EV

All other transport will have the same efficiency 51% and so will require 7 TWh hydrogen.

3.3. Inland shipping and fishing: hydrogen fuel cell based electrical propulsion.

This type of transport is fully transferred to electrical propulsion. The H2 fuel cell based electrical propulsion system will have an average efficiency of 56%. So, the required hydrogen will be: 22 TWh hydrogen.
The FCEV vehicles and ships require strongly compressed hydrogen from 250 up to 700 bar enabling a good distance range. High pressure hydrogen pump stations have been added in the system design for that reason. A typical group of hydrogen compressors are ionic compressors. Hydrogen pump stations therefore have an additional electrical demand of 10% of the compressed hydrogen energy content, resulting in an additional 5 TWh electricity demand.

3.4. Domestic aviation: standard combustion using green kerosene.

We assume the gross energy demand 2050 will be about the current (2015) demand for the domestic aviation.
Electric propulsion is still not considered to be an appropriate engine system for the aviation sector -inland and international and the fossil kerosene has to be replaced by a green type of kerosene. Biomass based kerosene is a way for production of green kerosene, but as we explicitly reserve biomass as the basis feed stock for the chemical industry, biomass-based kerosene is no option in het energyNL2050 plan.
Another option is the aviation fuel production by synthesizing the kerosene from hydrogen and coal monoxide. Producing the hydrogen and coal monoxide both from green electricity results in the production of green kerosene. See for this production technology more explanation in the main part, section 3.4 and based on the results in this explanation, the estimated fuel demand in 2050 for the inland aviation is 3 TWh green kerosene. Production will require 0.9 TWh hydrogen and 2.7 TWh electricity.

3.5. Summarizing these 2050 results for the transport function

	2015	**2050**	
	Fossil based	**electricity**	**hydrogen**
Transport type	TWh	TWh	TWh
. Passenger cars:	74	25.5	
. lighter road transport:	15	5	
. heavy road transport:	22		16
. other road transport	10		7
. fishing and domestic shipping:	30		22
. domestic aviation: 0.25 Mton kerosene	3	2.5	1
	+----	+-----	+----
Total energy demand Transport	154 TWh	33 TWh	46 TWh

. For the hydrogen compression an additional 5 TWh electricity is necessary.
. The 2050 domestic aviation requires 3 TWh kerosene. Production requires 2,5 TWh electricity plus 1 TWh hydrogen.

Table B5: Fuel demand Transport 2050 compared with demand 2015

1.
2.

Appendix C: Outline derivations from CBS energy balance

1. Introduction

We have derived the final energy demand in the Netherlands from the CBS Energy Balance using the Open Data APIs. Our calculations are documented in a Jupyter Notebook (ref. 29), available upon request.

2. Datasets used

Specifically, we use four data sets:

1. Energy balance sheet; supply and consumption, sector
2. Energy balance sheet; supply, transformation and consumption
3. Emissies naar lucht op Nederlands grondgebied; wegverkeer
4. Emissies naar lucht op Nederlands grondgebied; totalen

Python (ref. 30) with the Pandas library (ref. 31) is used to perform the calculations.

CBS presents the energy balance according to their multi-level sector definition (ref. 32). The Energy Commodities (EC) are (also) represented according to a hierarchical tree.

In the analysis we follow the approach outlined in "Het energieverbruik voor warmte afgeleid uit de Energiebalans", R Segers, CBS 2009 (ref. 33). This document explains how to convert the data the Energy Balance Sheet to get a segmentation in electricity, heat, transport fuels and feedstock (non-energetic use of energy commodities). Electricity, transport fuels and feedstock can be directly derived from the Energy Balance. In principle heat is calculated by taking the sum of all final usage of Energy EC minus electricity and transport fuels.

Some corrections and additions are necessary: Firstly, CBS does not report energy consumption by mobile agricultural and building equipment as transport. However, they do report the usage of typical transport fuels for these sectors. We correct for this in the same way as indicated in the above-mentioned paper. Secondly, there is no further segmentation for road transport. For this we used the dataset on emissions, wegverkeer by applying the proper factors to the reported CO_2 emissions. Thirdly the energy balance only includes data about aviation and shipping with both origin and destination in The Netherlands. The dataset on emissions, total can be used here by again applying the appropriate conversion factors. Finally, with respect to heat, we have to distinguish between Low-Temperature (below 100C) and High-Temperature heat. Domestic Transport and Other sectors do not use High-Temperature Heat. We are interested in the low temperature (below 100C) heat fraction of the industrial sectors. As this is not included in the CBS data, we had to use an alternative source and based ourselves on the analysis of Table 3 of "Duurzame warmte en koude in Nederland", ECN 2009. In summary: Oil Refineries: 0%, Chemical: 5%, Metal 15%, Other Industry 29%.

The Energy Balance considers the Crude Oil Refineries, the Cokes ovens and the Blast Furnaces for steel manufacturing as part of the Energy Sector. Energy Commodities are transformed from one kind to another, e.g., crude oil to petroleum products, coal to cokes, cokes and iron ore to steel. The net energy lost in these processes is reported and considered in our analysis as "non-thermal" use.