KIVI
Engineering Society

Koninklijk Instituut Van Ingenieurs

The future Dutch full carbon-free energy system

A design study
KIVI section Electrical Engineering

December 2017

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Dutch Summary

Met wind en zon komen we ver

De energievoorziening kan op basis van wind en zon, mits we dat combineren met grootschalige dagopslag en een fors volume aan waterstof als buffer. Dat is de kern van het energieplan dat is opgesteld door het KIVI-researchteam EnergyNL2050.

Het energieplan is samengesteld door dr.ir. Eric Persoon, ir. Loek Boonstra, ing. Paul van Moerkerken en dr.ir. Steven Luitjes. Dit researchteam baseert zijn energieplan op een lange reeks lezingen die het organiseerde met deskundigen uit de energiewereld, zowel van onderzoeksinstituten en universiteiten als van bedrijven. Eerder hadden ze al ideeën uitgewerkt voor alleen de elektriciteitsvoorziening, nu is er een duurzaam alternatief voor het complete energiesysteem. Hieronder volgt een samenvatting.

Wat wordt onze energiebehoefte?

Het KIVI-plan gaat ervan uit dat er in 2050 flink minder energie nodig is. Dat is vooral te danken aan het voorkomen van omzettingsverliezen en verandering van industriële processen. Zo heeft elektriciteit produceren met gas of kolen een maximaal rendement van zo'n 50 %, de rest verdwijnt als warmte. Met zonnepanelen en windturbines zijn die omzettingsverliezen veel kleiner, hooguit 10 %. Dat levert dus direct een besparing van zo'n 40 %. Dat geldt nog sterker voor transport: een auto op benzine of diesel haalt met moeite een tank-to-wheel efficiency van zo'n 25 %, bij elektrische aandrijving is dit 80 % voor een batterij-EV en voor een H2 brandstofcel-EV nog altijd meer dan 45 %.

Iets soortgelijks geldt voor de bestaande industriële processen. Zo kost het raffineren van ruwe aardolie veel energie; dat hoeft in een fossielvrije energievoorziening niet meer. Destillatieprocessen die nu veel warmte gebruiken worden vervangen door scheidingstechnieken met behulp van membranen. Proces warmte tussen de 100-200 °C graden kan worden opgewekt met industriële warmtepompen die aanzienlijk minder energie nodig hebben dan bij verhitten met aardgas.

Alles bij elkaar gaat het plan ervan uit dat er in 2050 de helft minder energie nodig is dan in 2012. De tabel hieronder geeft een overzicht van de energievraag in 2015, de energievraag in 2050 zonder transitie naar duurzaam (Business as Usual), en de energievraag volgens het KIVI-plan.

De totale energievraag is vergelijkbaar met energiescenario's van bijvoorbeeld Greenpeace en Urgenda, en veel gunstiger dan recente prognoses van het Planbureau voor de Leefomgeving en het energieonderzoekscentrum ECN.

Om in die totale energiebehoefte te voorzien is er in 2050 een hoeveelheid van 400 TWh elektriciteit nodig (inclusief productie van waterstof (100 TWh) voor de hoge temperatuurwarmte en de transportsector en omzettingsverliezen (60 TWh)). Momenteel is het elektriciteitsgebruik zo'n 120 TWh. Het energiesysteem zal dus verregaand elektrificeren. Die verandering gebeurt vooral bij het produceren van warmte, in het transport en bij industriële processen.

Energie2050	2015	BAU 2050	energieplan 2050
	TWh	TWh	TWh
Licht + apparaten	119	120	127
Netverliezen	4	4	19
Curtailment			2
Transport	155	170	70
Lage T warmte	200	211	43
Restwarmte			(40)
Hoge T warmte	160	168	78
Warmteverlies centrales	110	110	
Omzettings- en warmteverliezen			60
Totaal	748	783	399

Hoe komen we aan warmte?

Nu gaat dat met aardgas, en dat zal compleet veranderen. Voor de lage temperatuurwarmte van < 100 °C gaat dat voor een deel elektrisch gebeuren met warmtepompen, zoals die nu al in nul-op-de-meter gebouwen gebruikelijk zijn. Daarnaast zijn er warmtenetten. Die worden dan niet meer zoals nu gevoed door elektriciteitscentrales of afvalverbrandingsovens, maar door installaties die moeten koelen (pakhuizen, datacenters, supermarkten, enzovoorts), door de warmte die vrijkomt bij het produceren van de waterstof en door warmte die de industrie over heeft.

De hoge temperatuurwarmte van >100 °C in de industrie wordt elektrisch geproduceerd, zo nodig met waterstof.

Welke energie gebruikt het transport?

Elektrificatie van persoonsvoertuigen ligt voor de hand, daar is nu al een begin mee gemaakt. Elektrisch rijden is ook veel efficiënter dan rijden op fossiele brandstof.

Voor zwaar transport zou rijden op batterijen het transport nog eens extra zwaar maken. Daarom maakt die gebruik van waterstof en een brandstofcel waarin die waterstof wordt omgezet in elektriciteit. Dat gaat gepaard met omzettingsverliezen, de efficiency van de totale cyclus is zo’n 47 %, maar dat is altijd nog twee keer beter dan bij gebruik van diesel.

Bij de scheepvaart geldt hetzelfde: elektrisch varen met waterstof en een brandstofcel.

De luchtvaart is veel lastiger te elektrificeren, want daar speelt gewicht een doorslaggevende rol, en waterstoftanks en batterijen zijn zwaar. Hier brengen synthetische brandstoffen uitkomst, gemaakt van CO2 dat bijvoorbeeld vrijkomt bij gebruik van biomassa als grondstof in de chemische industrie. Er is dan grosso modo geen netto-uitstoot van CO2.

Waarmee produceren we die energie?

Wind en zon zijn de belangrijkste bron, zij leveren samen 85 %. Voor de rest komt 10 % van duurzame import, bijvoorbeeld in de vorm van waterstof uit landen die een overschot aan elektriciteit hebben, en 5 % komt van andere bronnen als geothermie, getijdencentrales, enzovoorts.

Zon levert zo’n 17 % van het totaal. Daarvoor is 78 GW aan zonnevermogen nodig. Ruimte daarvoor is te vinden op daken van woningen, kantoren en bedrijfsgebouwen, langs (spoor)wegen, en zonneparken op land of water.

Windenergie is goed voor 68 % van het totaal. Daarvoor komt 6 GW aan windturbinevermogen op land te staan, de doelstelling van het huidige energieakkoord. Meer windturbines op land is gezien de ruimtelijke impact niet haalbaar. Op de Noordzee komt 63 GW aan windvermogen. Door gebruik van windturbines met een vermogen van 10 – 15 MW, duidelijk veel groter dan die er nu staan, is een windparkdichtheid van 7 MW/km² haalbaar. Voor het gewenste windvermogen is dan een oppervlak van 9000 km2 nodig. De windturbines leggen daarmee beslag op een zesde van het totale oppervlakte van Nederlandse deel van de Noordzee.

Wind en zon leveren niet constant

De opbrengst van zon en wind is niet constant. Zon wisselt sowieso per etmaal, daarnaast veranderen weersomstandigheden voortdurend, en is er een verschil in opbrengst tussen de seizoenen. Over een jaar gemiddeld is er met het opgestelde vermogen voor wind en zon in 2050 zo’n 5000 uren per jaar een overschot aan elektriciteit, de opbrengst zal gedurende zo’n 4000 uur in een jaar tekort schieten. Dat tekort kan soms wel een maand achter elkaar voortduren. Er zal dus het nodige moeten gebeuren om het energiesysteem in balans te brengen.

Vooral op kortdurende wisselingen, zoals dag nacht, is in te spelen door de vraag naar energie aan te passen. Een koelhuis kan ook wel een tijdje zonder stroom, de auto kan soms ook best wat later opladen, en eenmaal opgewarmd water kan in een geïsoleerd vat dagen mee. Het totale effect ervan is lastig te bepalen, daarom houdt het energieplan er nu geen rekening mee. Voor seizoenswisseling is vraagaanpassing sowieso niet geschikt. Wat moet er dan wel gebeuren?

Seizoenswisseling opvangen met de goede mix

Voor de seizoenswisselingen is gezocht naar een mix tussen zon- en windopbrengst die jaarrond optimaal produceert. Per seizoen verschilt de opbrengst van elk afzonderlijk flink: voor de zon is de verhouding tussen zomer- en winteropbrengst 7:3, voor wind 4:6. Tegelijkertijd is er vooral in de winter behoefte aan lage temperatuurwarmte: er moet in de winter dus meer energie worden geproduceerd dan in de zomer. De ideale wind-zon-mix blijkt nu 4:1, dus vier keer meer windenergie dan zonne-energie. Die verhouding zorgt ervoor dat de extra-productie van windturbines in de winter voldoende is om aan de extra wintervraag te voldoen en de lagere opbrengst van de zonnepanelen op te vangen. De noodzaak tot seizoensopslag wordt daardoor geminimaliseerd.

Korter durende wisselingen opvangen met dagopslag

Het dag-nachtritme van zonne-energie wordt voor een goed deel opgevangen met dagopslag. Overdag schijnt de zon en is er minder vraag, de batterij levert wat nodig is aan het begin van de avond. Die dagopslag kan ook snelle fluctuaties in wind- en zonopbrengst opvangen. Vooral voor de zonnepanelen is dat belangrijk, want die kunnen bij een zonnig weer zorgen voor een hoge piekopbrengst. Afgestemd op dat zonvermogen rekent het plan met een sterk gedecentraliseerde opslagcapaciteit in de ordegrootte van 115 GWh, dat is de opbrengst die de panelen midden op de dag gedurende zo'n drie uur produceren wanneer overal de zon op z'n heetst schijnt. De opslag helpt zo de piekopbrengst op te vangen en kortdurende fluctuaties in de elektriciteitsproductie van wind en zon samen.

Een flink deel van die opslagcapaciteit kan worden geleverd door de accu van de elektrische auto. Om een idee van de omvang te krijgen: dat komt neer op 2 miljoen voertuigen met een batterij van 60 KWh, rekening houdend met de vooruitgang in batterijtechnologie. Ondenkbaar is het niet, wanneer er in 2030 geen voertuigen meer mogen zijn die rijden op fossiele brandstoffen.

Langer durende wisseling met een back-up systeem

Dan zijn er nog de langer durende fluctuaties, bijvoorbeeld een maand lang nauwelijks opbrengst van wind en zon. Om het effect van dat soort langdurende fluctuaties in kunnen te schatten gebruikt het energieplan de opbrengststatistiek van wind en zon in ons land. Die geeft aan hoeveel uur er in het jaar maximaal wordt geproduceerd, hoeveel gemiddeld en hoeveel heel weinig tot haast niks.

Daaruit blijkt dat wind en zon gedurende 5000 uur een overschot leveren, en een kleine 4000 uur te weinig produceren. In het energieplan wordt dat overschot gebruikt om extra waterstof te produceren, dus bovenop de elektriciteit die al wordt gebruikt om in de waterstofvraag van industrie en zwaar vervoer te voorzien.

De periode dat er een tekort is heeft twee gevolgen. In eerste instantie is er nog wel voldoende stroom voor de directe elektriciteitsvraag, maar onvoldoende om in de waterstofvraag te voorzien. De opgebouwde waterstofreserve springt dan in. Daarvoor is dan ongeveer de helft van dat overschot nodig.

En dan is er een periode, in totaal zo'n kleine 1000 uur per jaar dat er ook voor de directe elektriciteitsvraag een tekort is. De rest van het waterstofoverschot wordt dan gebruikt om met brandstofcellen elektriciteit te produceren.

Dit laatste is dus het back-upsysteem dat standby staat wanneer gedurende een langere periode zon en wind het laten afweten. Uiteindelijk moet dat back-upsysteem in een hoeveelheid energie voorzien die 4 % is van wat jaarlijks in totaal wordt geproduceerd. Het moet wel een flink vermogen kunnen leveren, ruim 20 GW. Het zal dus, net als elk back-upsysteem, jaarrond slechts beperkte tijd volop produceren. Met het verminderen van de vraag naar stroom in tijden van gebrek aan vermogen door windstilte of weinig zon, bijvoorbeeld door grootverbruikers, is in het plan geen rekening gehouden. Dit zou het back-up probleem wel aanzienlijk verminderen. Daarnaast kan import soelaas bieden.

Het energieplan rekent met gemiddelde opbrengsten van wind en zon. In de praktijk zullen die het ene jaar wat hoger zijn en het andere lager. Volgens de statistiek is de opbrengst in een ‘slecht’ jaar zo’n 6 % onder het gemiddelde. Doet dat zich voor, dan moet import soelaas bieden.

Summary

We'll go far with wind and solar

It is possible to secure our energy supply with wind and solar power, as long as we combine this with large-scale daily storage and large volumes of hydrogen as a buffer. That's the main message of an energy plan drawn up by the
KIVI research team, EnergyNL2050.

The energy plan has been compiled by dr. ir. Eric Persoon, ir. Loek Boonstra, ing. Paul van Moerkerken and dr. ir. Steven Luitjens. This research team based its energy plan on a long series of lectures organised with experts from the energy sector; not only from research institutes and universities but also from companies. They had already developed ideas for an electricity supply, but have now provided a sustainable alternative for the complete energy system. A summary is given below.

What will our energy demand be?

The KIVI plan assumes that by 2050, we'll need a lot less energy. That's primarily due to the prevention of conversion losses and changes to industrial processes. Electricity generation using coal or gas, for instance, has a maximum efficiency of 50%, with the rest dissipated as heat. The conversion losses of solar panels and wind turbines are much lower, at no more than 10%. That's a direct saving of some 40%. This applies even more so to transport: a car running on petrol or diesel manages at best a tank-to-wheel efficiency of some 25%, with electric cars running at 80% with a battery EV, and H2 fuel cell EVs still managing more than 45%.

It's a similar story with industrial processes. The refining of crude oil requires a lot of energy, but that's no longer necessary with a fossil-fuel-free energy supply. Distillation processes that now use large amounts of heat are replaced by separation techniques using membranes. Process heat between 100–200°C can be generated using industrial ground-source heat pumps that require much less energy than when heating with natural gas.

All things considered, the plan assumes that by 2050 we will need less than half the energy we did in 2012. The table below gives an overview of energy demand in 2015, energy demand in 2050 without transition to sustainable sources (business as usual), and energy demand according to the KIVI plan.

The total energy demand is comparable to energy scenarios of Greenpeace and Urgenda, for instance, and is much more optimistic than recent prognoses from the Netherlands Environmental Assessment Agency (PBL) and the Energy Research Centre (ECN).

To meet the total energy demand, 400 TWh of electricity will be required by 2050 (including the production of hydrogen (100 TWh) for high temperature heat demand and the transport sector, and conversion losses (60 TWh)). Electricity consumption is presently 120 TWh. So the energy

EnergyNL2050	2015	BAU 2050	energy plan 2050
	TWh	TWh	TWh
Lighting + devices	119	120	127
Grid losses	4	4	19
Curtailment			2
Transport	155	170	70
Low T heat	200	211	43
Residual heat			(40)
High T heat	160	168	78
Heat loss at power stations	110	110	
Conversion and heat losses			60
Total	748	783	399

system will be subject to extensive electrification. This change will focus specifically on the production of heat, on transport and on industrial processes.

So how do we obtain that heat?

This is currently done using natural gas, but that will have to change radically. Low temperature heat of < 100°C will be partially produced electrically using ground-source heat pumps, such as is already the case with zero-at-the-meter buildings. Then there are the heat grids. These will no longer be fed from power stations or waste incinerators, but by systems designed to provide cooling (warehouses, data centers, supermarkets, etc.), using heat generated from hydrogen production and excess heat from industry.

The high temperature heat of > 100°C in the industry sector will be produced electrically, using hydrogen if necessary.

Which energy does transport use?

The electrification of private vehicles is self-evident, and we've already started down that road. Electric cars are also much more efficient than cars that run on fossil fuels.

For heavy transport, running on batteries would make it even heavier. That is why fuel-cell power is used in this application, with hydrogen being converted into electricity. And that goes hand in hand with conversion losses, with the efficiency of the total cycle at 47%, yet that's still two times better than diesel.

And the same goes for shipping: electrical power from hydrogen and a fuel cell.

Aviation is much more difficult to electrify, as weight plays a decisive role, and hydrogen tanks and batteries are heavy. Synthetic fuels made of CO2 could be a solution here, using carbon dioxide for instance released from the use of biomass as a raw material in the chemical industry. By and large, this could then result in zero net CO2 emissions.

How do we produce this energy?

Wind and solar are the key sources, together supplying 85%. Otherwise, 10% comes from sustainable imports, for instance in the form of hydrogen from countries with surplus electricity, and 5% from other sources such as geothermal energy, tidal plants, etc.

Solar supplies 17% of the total. This requires 78 GW of solar energy. The space for this can be found on the roofs of homes, offices and commercial buildings, along roads and railway lines, and in solar parks on land or water.

Wind energy accounts for 68% of the total. This requires 6 GW of wind-turbine capacity on land, the target of the current energy treaty. More wind turbines on land are not considered feasible due to the spatial impact. Some 63 GW of wind power is to be installed on the North Sea. By using wind turbines with a capacity of 10 – 15 MW, clearly much larger than those currently installed, a wind farm density of 7 MW/km2 is feasible. A surface area of 9000 km2 is required for this wind capacity. The wind turbines would take up one sixth of the total surface area of the Dutch zone of the North Sea.

Wind and solar do not supply constant power

The yield from solar and wind is not constant. Sun of course has a diurnal pattern, weather conditions change constantly, and there are seasonal differences in yield too. By 2050, there will be an average of some 5000 hours a year of surplus electricity with the current annual installed capacity for wind and solar; this means a shortage for about 4000 hours a year. That shortage could sometimes last for as long as a month. So a lot of work is required to balance the energy system.

Especially with regard to short-term changes, such as between day and night, the demand for energy can be adapted to respond to this. A cooling unit can run for a while without power, cars could easily be charged later at night and, once heated, water stays warm for days in an insulated vessel. The total effect of this is difficult to determine, which is why the energy plan doesn’t yet factor this in. For seasonal differences, demand adjustments are not appropriate at all. So what needs to happen instead?

Absorbing seasonal differences with a good mix

For seasonal differences, we looked for a mix between solar and wind yield that provides optimum power generation all year round. The yield for each season differs substantially: the yield ratio between summer and winter for solar is 7:3, but is 4:6 for wind. At the same time, there is demand for low temperature heat in winter in particular; so in winter more energy must be produced than in summer. The ideal wind-solar mix turns out to be 4:1, four times more wind energy than solar energy. That ratio ensures that the extra production of wind turbines in winter is sufficient to meet extra winter demand and absorb the lower yield from solar panels. This minimizes the need for seasonal storage.

Absorbing changes of a shorter duration with daily storage

The day-night rhythm of solar energy is largely absorbed with daily storage. During the day there is sun and lower demand, and batteries supply what is needed in the early evening. This daily storage means that rapid fluctuations in wind and solar yield can be absorbed. And that is particularly important for solar panels, as these can generate peak yield during sunny weather. Geared to that solar capacity, the plan factors in a highly decentralised storage capacity in the order of 115 GWh. This is the yield that the panels produce for around three hours in the middle of the day when the sun is at its highest point. The storage helps to absorb peak yield and short-term fluctuations in electricity production of wind and solar combined.

A significant part of the storage capacity can be supplied by the batteries of electric cars, which corresponds with some 2 million vehicles containing a 60 kWh battery. This is not unthinkable, especially if fossil-fuel powered cars would be banned by 2030.

Longer-term changes require a back-up system

Then there are the longer-term fluctuations, for instance a month-long low yield from both solar and wind. To estimate the impact of that type of long-term fluctuations, the energy plan uses the wind and solar yield statistics for the Netherlands. These indicate how many hours are produced at most in a year, how many on average and how many hours there are in which barely any power is generated.

This suggests that wind and solar produce a surplus for 5000 hours, and too little for some 4000 hours. In the energy plan, that surplus is used to produce extra hydrogen, in addition to the electricity that is already used to meet demand for hydrogen from industry and heavy transport.

The period in which there is a shortage has two consequences. Initially, there is sufficient power for direct electricity demand, but not enough to meet demand for hydrogen. The accrued hydrogen reserve is then deployed. This requires around half of the surplus.

And then there is a period – in total around 1000 hours a year – during which there is also a direct shortfall in meeting electricity demand. The rest of the hydrogen surplus is then used to produce electricity using fuel cells. This is therefore the back-up system that is on standby when solar and wind yields fall short for longer periods. Eventually, the back-up system has to provide energy that equates to 4% of the total annual energy production. It has to be able to generate a substantial capacity, at over 20 GW. As with any back-up system, it would only produce at full capacity for limited periods during the year. The plan does not take account of a reduction in demand for power in times of a lack of capacity due to a lull in the wind or too little sun, from for instance major consumers. This would of course substantially reduce the back-up problem. In addition, energy imports could be a solution.

The energy plan factors in the average yields of wind and solar. In practice, these will be higher in some years and lower in others. According to the statistics, the yield in a ‘poor’ year is some 6% below average. In such cases, energy imports would be a solution.

Introduction

The intent of this paper is to analyse the system aspects of the Dutch energy system in the further future (around 2050). It is not the intent to cover all the issues that will arise in the transient period from now on until the final energy system. It is expected that the future energy system will look very different from the current system and there is a danger that we may extrapolate the current situation rather than to look at a new system. Several studies have already been done on the expected future energy requirements and we will use the data from those studies. Also the possible energy sources are already well documented. We will use all those data as well.

Data have been collected during the symposia on the future Dutch electric power system (Ref. 1, EU-2050 Powerlab), future home (Ref. 2, Homelab2050) and future Dutch energy system (Ref. 3, EnergyNL2050) organized by KIVI (Royal Dutch Society of Engineers) in the period of 2013 - 2017. Important input also has been the advice of the RLI (Ref. 4 - Council for the Environment and Infrastructure) to the Dutch government and the related report from CE Delft on energy and CO2 emissions in 2050 (Ref.5). Also two German reports have provided a lot of useful information (Ref. 7 and Ref. 10) .

Besides designing a carbon free system we have focused on four main design objectives:

- develop a regional view where most of the used energy resources are available in the Netherlands without relying too much on energy supplies from other countries.
- having a design that has zero excess energy produced in the winter months or the summer months, avoiding the need of seasonal energy storage
- working with a demand side that is electrified to a very large extent
- having a very high percentage of renewable energy

The Paris agreements aim at a maximum temperature increase well below 2 degrees . There are serious indications that this implies zero CO2 emission in 2050. Therefore we will examine here the possibility of a zero CO2 emission energy system. We can achieve this except for airplanes where we will need to make synthetic jet fuel. The needed CO2 for this can be extracted from the air to become CO2 neutral . In fact we want to achieve that without CCS and therefore make the entire energy system carbon free.

Although we started the design study from a regional point of view, we are still aware of the significant importance of the international energy exchange in the coming decades. See our remarks in section 6.

We will divide the study in several parts. We will start with a discussion of the energy sources in part 1. In part 2 and 3 the energy users and the mix of sources will be analyzed. For the stability of the energy system, backup and flexibility see part 4, 5 and 6. In parts 7, 8 and 9 are the conclusions and appendices with detailed results.

1. The used energy sources: the main sources PV and Wind

The energy sources (abbreviated with RES) that appear as important candidates are wind, PV, biomass, natural gas (with CCS), coal (with CCS) and geothermal energy. In this study we would like to eliminate biomass as an energy source. Biomass can better be used as feedstock for the chemical industry. Moreover our country is very densely populated and the relative amount of biomass is very limited compared to our energy needs. Also it is very difficult to avoid misuse of biomass as an energy source. Then we have natural gas and coal with CCS. This could very well be a solution in the first transition period but not suitable for the final system. CCS on land is most likely not acceptable and at sea it may be rather costly. Moreover there is limited storage capacity for CCS and therefore not sustainable. Geothermal energy is also mentioned as a source for low temperature heat. We think that this will not be needed in the future or only to a very small extent. So we are left mainly with wind and PV. In this way we will also achieve a zero-carbon energy system with no CO2 emission.

Conclusion on energy sources

So in conclusion we will use mainly wind and PV for generating the required energy. There is the option to use also other energy sources like blue energy and tidal energy but those will produce only a limited amount of energy. In our design we include the import of about 10% green electricity to complement the own generated electricity. As another possibility, one may expect in the coming decennia, is the import of hydrogen or ammonia from countries where abundant sunshine- or wind energy is available. We will comment on this later. We still have to decide on the ratio between wind at sea and wind at land. We have a large part of the North Sea (1.5 times the size of the surface of the land, 57000 km2) and we have a very densely populated country. So we should put much more power at sea compared to at land. In our system proposal we use about 60 GW wind at sea and 6 GW wind at land. It is clear, electricity transport to the mainland is expensive. But there may be ways to reduce those costs as we will discuss later.

2. The expected energy users

We will follow the division that has been used in the recent past by many Dutch organizations (Ref. 4 CE Delft LRI report), dividing the energy demand in four energy functions: low temperature energy for temperatures below 100 degrees, high temperature energy for temperatures higher than 100 degrees, energy for the transport function and the electricity demand for lighting and appliances (but not including the electricity for heat pumps and electrical transport) .

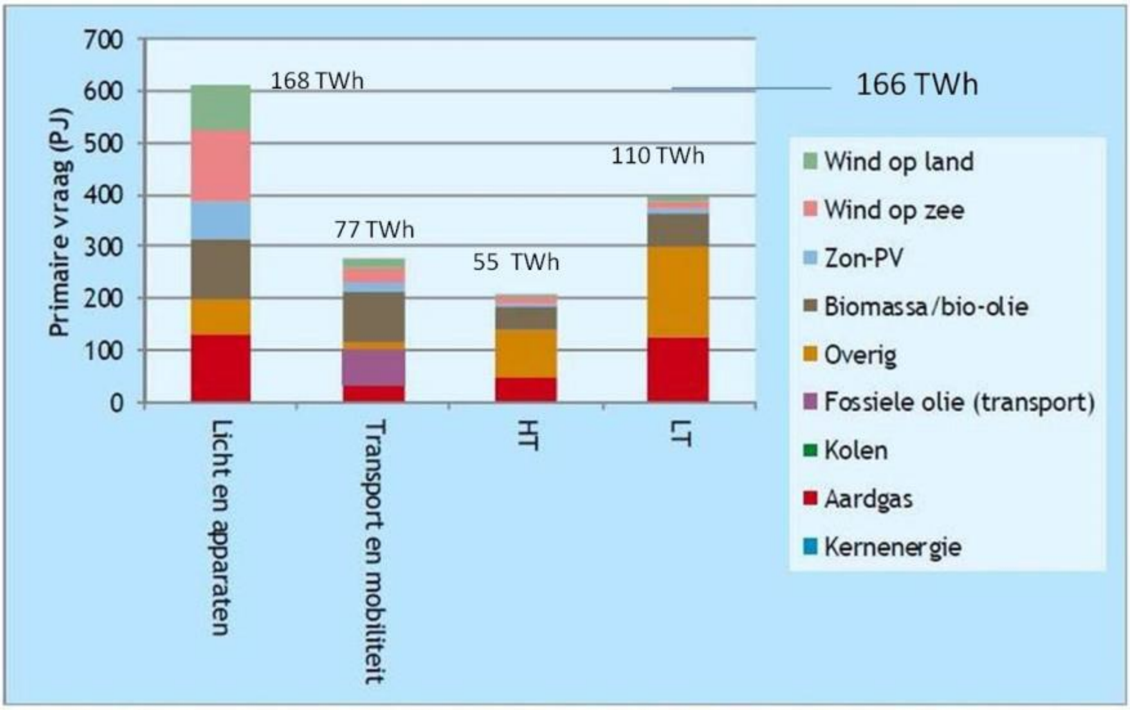
To estimate the demand for 2050 we have used the CBS data for 2015 and took into account an average energy saving of 1 percent a year and a yearly economic growth of about 1 percent (more exactly 1.15%). After 35 years this results in a constant energy demand in the future.

To repeat, the energy demand is divided in 4 sections as used in the CE Delft report (Ref. 5).
They are: lighting and electrical appliances, Low Temperature heat, High Temperature heat and transportation and mobility.

Notice that those are the primary energy demands. The final energy delivered may be much lower due to conversion losses. In our system design the conversion losses will be much lower in general because we do not use carbon fuels for those four sectors. The use of carbon fuels for electricity generation and also transportation results in very low efficiencies and therefore primary energy is much larger than the final energy used.

The TWh’rs for each energy function are given in the figure below (those are the primary energy demands) .

Figuur 16 **Primaire vraag per functie en bron 2050 Energy (R)evolution Scenario (PJ/jaar)**



Bron: Eigen berekening op basis van Greenpeace en EREC (2013). In deze figuur is het wel mogelijk

Figure 1: Energy demand according to Greenpeace R scenario

Three of the four functions are very close to our system proposal except one.

That is the first energy function which accounts for 610 PJ. This is the function that is served exclusively by electricity now (and will be also in the future) whereas the three other segments are now served by heat and fuels as well.

The 610 PJ corresponds with 168 TWh electrical energy. In the diagram half of this is supplied by PV and wind and the other half by biomass and gas. The 84 TWh , used by biomass and gas power plants, result in an electrical output of about 42 TWh (assuming 50 percent efficiency for those plants).

So the resulting available final electrical energy is 84 + 42 = 126 TWh. That is close to what we propose namely 127 TWh.

This is possible because of two main design approaches: First of all we choose a good balance between PV and wind and secondly we use a one-day battery storage system. For details see later. Both of those result in a situation where for more than 7000 hours the full load of all electrical needs can be supplied directly by the power delivered by PV and wind. Of the total energy, supplied in this way by PV and wind, close to 95 percent is used directly by end users. Only 5 percent needs to be provided by other means. See also the Power-to-Gas report (Ref. 9) and also Appendix C.

The needed energy demand may seem small compared to the energy we use now but the estimate in Figure 1 is realistic. One of the main reasons is that the energy is used which much less losses compared to the current situation. We will comment on that later, but a good example is transport where we propose to eliminate combustion engines which have a very poor energy efficiency. We will now discuss the four uses separately.

2.1 lighting and electrical appliances

This is the traditional use of electricity to power lighting and electrical appliances. It does not include the use of electricity in the other three sectors. Not much will change in the further future except that the appliances will use less electricity due to more efficient designs. We estimate a required demand of 127 TWh electricity, which also includes the energy used for cooling applications.

2.2 low temperature heat

This is the sector where energy is used for heating buildings, homes and greenhouses.
This is now mainly done by using natural gas. In the future this will change completely. Two methods will be used: using heat pumps that convert outside heat to heat usable for heating and also for providing hot water in homes and buildings. The other method will be to use heat nets that are fed by surplus heat from industry, power plants, and local warehouses and supermarkets. A lot of surplus heat is produced for cooling purposes that can be used to feed a heat net. Further on in this paper another source for heat nets will be discussed. It is the surplus heat that is produced when converting electricity to a chemical carrier by electrolysers (like hydrogen or ammonia).

More difficult housing locations
One point of attention is how to heat older homes and buildings in the crowded downtown areas of old cities and at the country side homes widely separated far from each other. Those last ones cannot be served by a heat net. During a cold week in the winter they may need a lot of electric power for heating. The electrical network to those homes may not be sufficient to handle the required power. But there are options to solve this problem without having to provide new power cables. A promising solution for both situations seems to upgrade the current natural gas pipes to carry hydrogen to those homes. If this is not economically realistic for the country side areas, a possibility also is to install hydrogen storage tanks at those homes and fill those either by hydrogen trucks or by local electrolyzers.

We estimate the total heat demand at 212 TWh. Using heat pumps with a COP of 4 we can provide 172 TWh using 43 TWh of electricity. The remaining 40 TWh heat can be obtained with the surplus heat from electrolyzer stations, the fuel cells power stations and industry. Also the use of heat storage buffers may be useful.

We need a lot of hydrogen in our concept and therefore also a lot of electrolysers, generating the hydrogen during a large part of the year (read Appendix C for the explanation). To be able to use the generated heat it may be advisable to locate those electrolysers close to (big) cities where heat nets will be used in the future. So in total we may need only 43 TWh of electricity. That is also close to the primary energy requirement.

The Greenpeace scenario requires 110 TWh of primary energy. That is because very little electricity is used and therefore the use of heat pumps is very limited.

2.3 high temperature heat

This sector needs heat at temperatures that cannot be provided by heat pumps. Studies are on the way to make heat pumps that produce heat at high temperatures (up to 150 degrees). It is not certain what can be achieved in the future but a large part of this heat cannot be provided by heat pumps. We foresee the two following methods in the future: electric heaters and hydrogen or ammonia burners. We focus here on the primary use of electric heaters for applications that require the high temperatures. They should supply 26 TWh of heat, using the same amount of electricity.

Two important industrial processes are producing a lot of CO2 emission: the ammonia industry with about 2 Mton CO2 per Mton ammonia produced and the production of basic steel also with an emission of 2 Mton CO2 or more per Mton basic steel.

- **The ammonia production** is based on the synthesis of N2 with H2. The hydrogen is produced nowadays by methane with a steam reforming process, responsible for the large CO2 emission. By replacing the production of hydrogen by electrolysis of water with green electricity 100% green ammonia will be produced. For the expected 3,7 Mton ammonia demand 26.5 TWh hydrogen will be necessary.
- **Basic steel processing.** We want to include another industrial process, the making of iron from iron ore (reference 10) . This is now done by burning cokes as the reducing agent and responsible for the large CO2 emission. For the transfer to a green process with zero CO2 emission, the cokes should be replaced by hydrogen as the reducing agent. About 22 TWh of hydrogen will be required to produce 7 Mton of basic steel a year. (see pages 137/138 of Ref 10). See also the presentation of Hans Kiesewetter (Ref 20) and the Swedish LKAB/Vattenvalls project “CO2 emission free ironmaking” (ref 24).
- **Other parts of industry.** In other parts of industry, we estimate that 3.5 TWh will be used.

2.4 Transport

There are several types of transport, transport by cars and trucks on roads, transport by trains, transport by ships and transport by planes. Most of the transport nowadays is based on combustion type engines, with an average tank-to-wheel efficiency lower than 20%. The massive switch to electric drive systems (electric vehicles, EV’s) will give an enormous energy demand reduction! Battery EV, with a tank-to-wheel efficiency of 80% will result in a factor 4 better efficiency. Heavy transport and shipping, that will use predominantly fuel cell based EV drive systems, will have a tank-to-wheel efficiency better than 40%. In our scenario therefore is chosen for a complete transfer to battery based or fuel cell based EV engine systems, except for air transport.
The different transport types will now briefly considered.

2.4.1 Road transport

It is already accepted that some parts of the road transport will be done by electric cars, busses and small trucks. The only difficult sector is (international) transport by heavy trucks. We foresee that in the future also this can be done electrically where the electricity is obtained by fuel cells that use hydrogen or ammonia. In our system proposal we propose to use only hydrogen. All needed technology to achieve this is already available. The extra advantage of such a solution is that the amount of unhealthy exhaust gasses or particles can be reduced drastically. Currently many projects focus on the production of CO2 neutral energy fuels like methane, methanol, formic acid etc.. If those fuels are burnt in combustion engines, the overall efficiently (from KWh to km driven) is lower than 20%. Our conclusion is that this should be avoided. The energy efficiency of formic acid will be better because fuel cells will be used in combination with electric motors.

2.4.2 Train transport

This will remain as it is now and require only electricity. Where currently diesel-based trains are used they could be converted to run on hydrogen, converting the hydrogen into electricity by fuel cells.

2.4.3 (International) Shipping and Fishery

For the international shipping and fishery the same motor drive technology can be applied as will be used for heavy road transport: electric drive trains using hydrogen as the fuel for fuel cells and electric motor drives. In that way sea transport will be completely carbon free. A second advantage is the large efficiency of the electric drive train, compared with the combustion drive. Due to that the 2050 hydrogen fuel demand for the shipping + fishery sector will be 14 TWh hydrogen. That is according to the CBS rules for the part in the Dutch energy use, where only the fuel used in the Dutch waters is taken into account.

2.4.4 (International) Air transport

This is the sector that will most likely still need carbon fuels. So CO2 emission from air transport is unavoidable. But when the fuel will be produced via synthesis of green Hydrogen with captured CO2 from air (or from sea-water!) or from a CO2 point source the transport function may be considered as carbon free!

In our scenario proposal the CO2 emitted during the use of biomass for production of bioplastics will be used in the synthesis process.

Again for air transport we only account for the transport inside the Dutch airspace resulting in a Dutch air transport demand of 3.2 TWh synthetic kerosene. The production process to produce this renewable synthetic kerosene requires about 0,8 Mton CO2 (coming from the biomass processing) and 6 TWh renewable hydrogen.

An important remark regarding the Dutch fuel production for the international shipping and air transport.
According to the CBS statistics 2015 for those international transport sectors the Dutch petrochemical industry produces 100 TWh fuel for the international shipping sector and another 100 TWh kerosene for the air transport sector, together 200 TWh fuel (16 Mton fuel). Although not an official part of the Dutch energy system, we must be aware that this huge fuel quantity has to be substituted by its green fuel alternatives, being in our scenario proposal hydrogen for the international shipping sector and synthetic kerosene for the air transport. The huge amount of energy required for this green fuel production has to be imported, when those green fuels should still be produced in the Netherlands.

Concluding:
Due to the massive transfer to electric based drive systems the transport sector will need 26 TWh of electricity and 44 TWh of hydrogen for transport. Current annual energy consumption by the transport sector is about 150 TWh carbon-based fuels with a CO2 emission of 40 Mton CO2.

Summarizing the total expected demand in 2050:
The total final demand as analyzed in the chapters above are

• Lighting and electrical appliances:	127 TWh
• Low Temperature heat: heat net 40 TWh plus 43 TWh for heat pumps:	83 TWh
• High Temperature heat: Hydrogen 52 TWh plus electricity 26 TWh:	78 TWh
• Transport: Hydrogen 41 TWh , 26 TWh electricity, 3.2 TWh renewable kerosene:	70 TWh

So the **final** demand for the four energy functions results in: 358 TWh: final electricity demand being 222 TWh, and final H2 demand 93 TWh. Together with the 6 TWh hydrogen for the production of the kerosene, total hydrogen demand is 99 TWh.

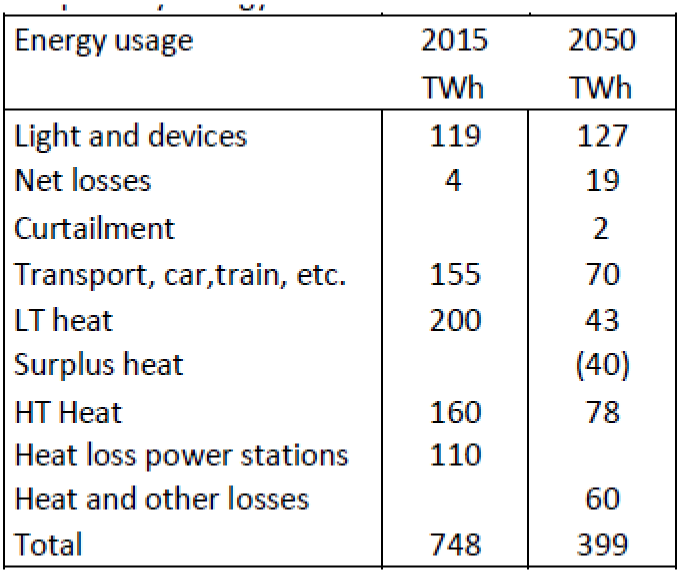
Be aware that this 99 TWh hydrogen is equal to 2,5 Mton hydrogen!

This hydrogen demand is generated by electrolysis. Including the electrolysis losses, compression and storage losses the electricity needed to generate this H2 demand is 140 TWh.

The H2-fuel cell backup system, delivering 12 TWhel annually , as described in part 4, requires another 28 TWh electricity for electrolysis. The electrolyser systems have to produce 133 TWh hydrogen, requiring 140+28=168 TWh electricity. The losses in all conversion systems and hydrogen transport plus storage can be calculated to be 60 TWh.

There are still some more losses to be added to this demand: net losses (5%) being 19 TWh, losses in the backup system 16 TWh, and some curtailment 2 TWh.

The primary energy demand described above is summarized in the following table:



Energy usage	2015 TWh	2050 TWh
Light and devices	119	127
Net losses	4	19
Curtailment		2
Transport, car,train, etc.	155	70
LT heat	200	43
Surplus heat		(40)
HT Heat	160	78
Heat loss power stations	110	
Heat and other losses		60
Total	748	399

Table 1: Summary of energy usage in 2015 derived from CBS data and the estimated usage for 2050

So it can be concluded that a total annual primary electricity demand, being 399 TWh, will result and should be covered by the renewable energy sources.

A detailed overview of the entire energy system can be seen in the system diagram in Appendix A.

3. The required mix of the energy sources

3.1 The required renewable energy sources

To obtain the required mix of renewable energy sources an accurate spreadsheet calculation has been applied. Important approach is to get a good insight in possible excess energy: short term and season-long related. Minimizing of the excess electricity is important because excess electricity should be converted in hydrogen, stored and re-used via re-electrification. To minimize the season related excess electricity the calculations are based on a summer part (April 1 to October 1) and a winter part (October 1 to April 1). Important is to have available good season based profiles for the energy sources and for the demand functions. This is explained in appendix B.

To get a good insight in the short term excess electricity, size and hours, a good tool is available with the power duration curves. See for details appendix C.

As a result appendix A shows the detailed high level block diagram with the demand figures at the right side of the diagram and the mix of energy sources at the left side. Starting with 40 TWh import electricity and 20 TWhel from some other renewable sources the contribution of the main sources Wind- and PV electricity has to be 326 TWh.

With a ratio of 4 between Wind-electricity and PV-electricity, these parts are:
- PV: 66 TWh / 78 GW
- Offshore Wind energy: 256 TWh / 63 GW
- Onshore Wind energy: 15 TWh / 6 GW

With this ratio 4 between the wind-electricity and the PV-electricity the seasonal excess electricity will be zero in an average year, an important result! This will be explained in the next section.

Be aware that the contribution of variable energy sources (wind and PV energy) is 85%! And this large part of highly variable renewable energy sources asks for much attention in the design of a stable and reliable energy system. The center of the block diagram shows the system for conversion to H2, temporary Storage and Backup Power Plant . These blocks will be discussed in the next sections.

Electricity import
In the block diagram an electricity import is shown of 4.5 GW delivering 40 TWh, about 10% of the total required energy. Looking to the energy from Wind power and PV, we think that these quantities are close to the upper level our country is able to produce. So some additional green energy import is required. See chapter 6 for some more remarks about energy import/export strategy.

Hydrogen import instead of electricity import
Instead of importing electricity , an interesting alternative which may become available in the coming decades, is importing hydrogen (or ammonia) by ship or pipelines from places where it is much cheaper to generate electricity from renewable sources compared to the Netherlands. One should think of places much closer to the equator, maybe in desert areas where ample sunshine is present and at offshore areas with constant, strong winds. When such an hydrogen economy will be grown to a worldwide level, cheap hydrogen will be available every time of the day. See ref (25) "Solar to the People", prof. Ad van Wijk, November 2017. Electricity can be generated from those by the fuel cell power plants.

Based on the above, a basic block diagram of our scenario is shown in following figure:

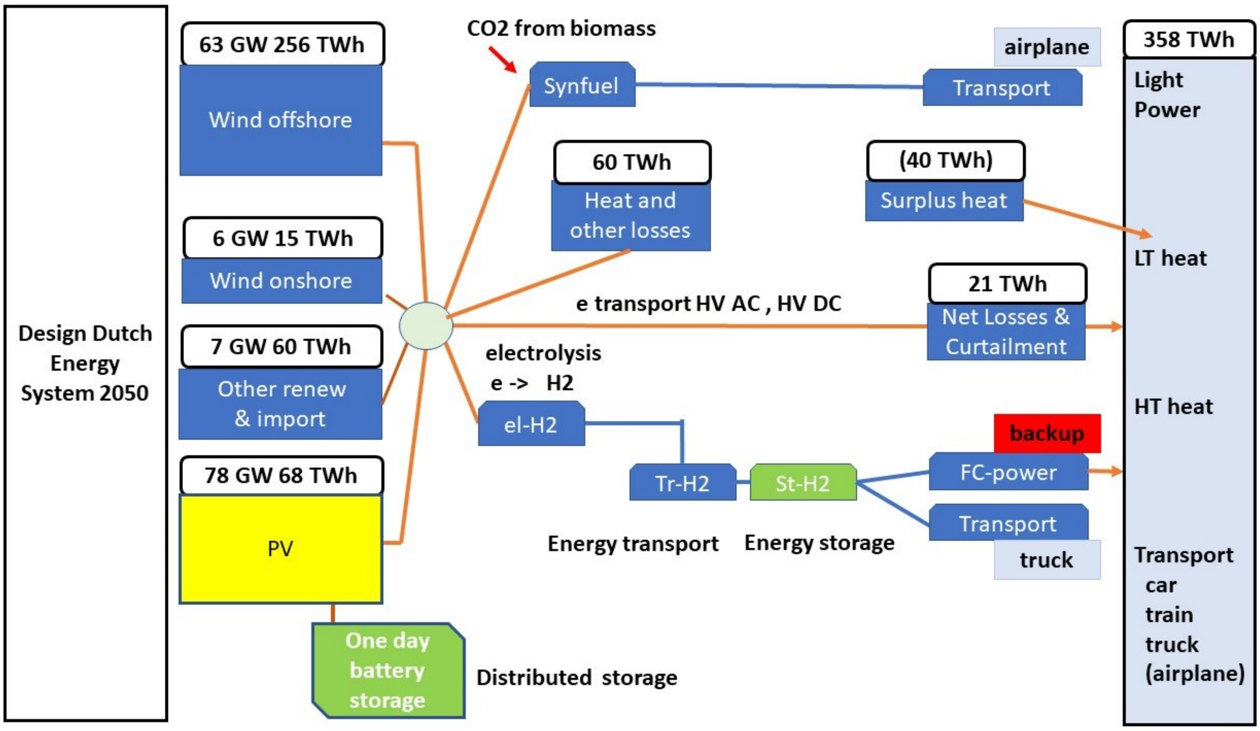


Fig 2. Simplified block diagram of the energy system NL2050. Total primary energy usage is 399 TWh. See diagram in appendix A for more details

3.2 The optimal ratio between wind and PV energy resulting in minimal seasonal excess energy

The three main renewable energy sources are wind on land, wind at sea and PV. These sources are strongly variable: variable from hour to hour, day to night and from summer to winter. Well known is the observation that PV energy and wind energy are more or less complementary over a year: much PV electricity in the summer and much wind electricity in the winter! This observation creates a possibility to minimize the difference of the produced electricity during the winter and summer months by searching for an optimal ratio between the Wind energy and PV-energy. For this analysis it is important to know the distribution between summer and winter energy from the variable energy sources.

This will also save a lot of energy for making the needed backup hydrogen and making electricity again from the hydrogen.

In German studies much attention has been given to those questions and in figure 3 from reference 7 this summer/winter distribution can be analysed , resulting in:

- PV-energy : summer /winter ratio at 70% /30%
- Wind energy : summer /winter ratio at 40% /60%

Those values seem to be reasonable ratios for the Dutch situation. Using those percentages we can calculate that, in order to achieve equal energy during summer and winter, a ratio of 2 is obtained (see also ref 22) . In a presentation by TenneT (Ref. 3) a preferred ratio of 2 is also suggested!

In our proposal however we have a higher energy demand in the winter months (for heating) than in the summer months, meaning more wind power compared to PV than the ratio 2 should be available. To analyse the optimal ratio between wind and PV energy, the summer/winter distribution for the various demand parts must be known. In appendix B these ratios are analysed. Using these figures the energy system calculation based on a summer/winter part the optimal ratio for the Wind/PV energy turns out to be 4.

So the energy production will be such that it matches the demand well regarding the summer/winter distribution, resulting in a minimal seasonal excess electricity being nearly zero!

In the appendix A detailed block diagram it can be seen that the summer excess electricity is zero. But we must be aware that this is just valid in an average year as the production from wind and PV is varying from year to year.

FIGURE 3 **MONTHLY FEED-IN FROM ALL RENEWABLE ENERGY SOURCES IN THE YEAR 2050 BASED ON THE METEOROLOGICAL YEARS 2006-2009 (MONTHLY AVERAGES).**

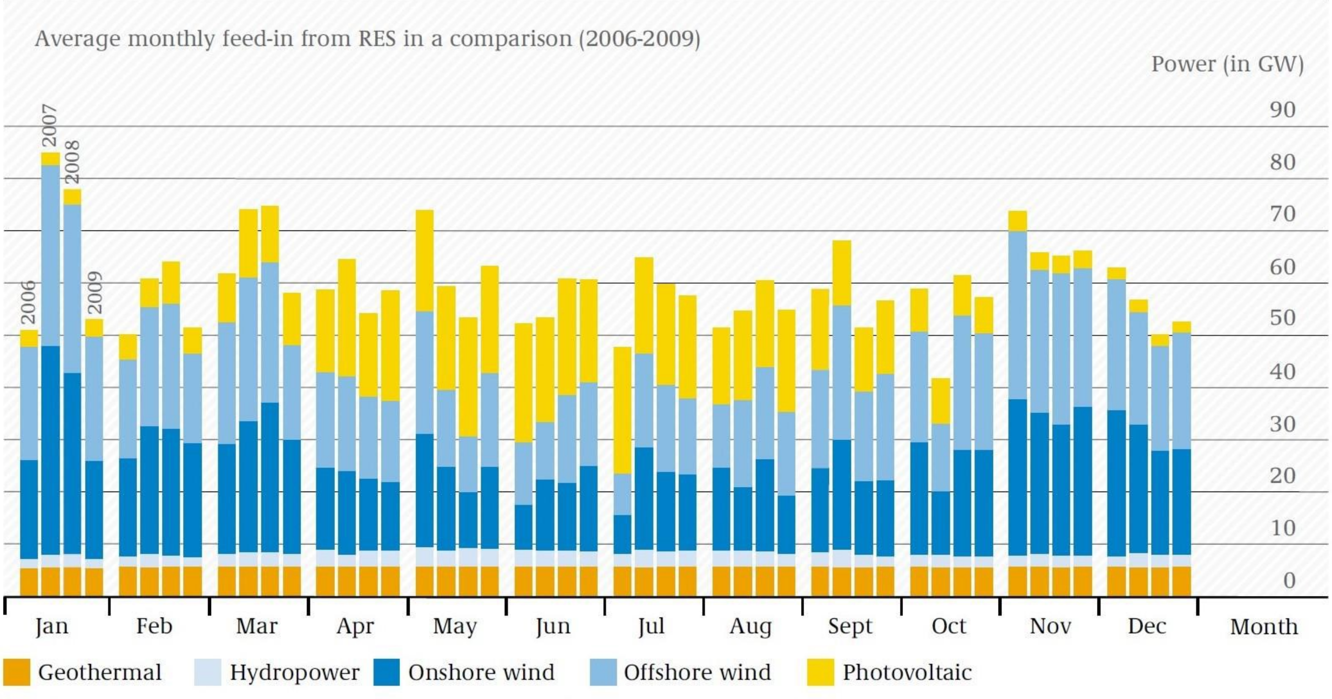


Figure 3: from reference 7

The above figure comes from the German report (Ref. 7) and shows how Wind and PV energy complement each other quite well. For clarity, we will not use Geothermal or Hydropower in our system proposal.

Designing the system with minimal seasonal excess electricity is strongly preferable, because it minimizes the amount of electricity that is needed to make hydrogen.

4. System flexibility: How to match supply and demand

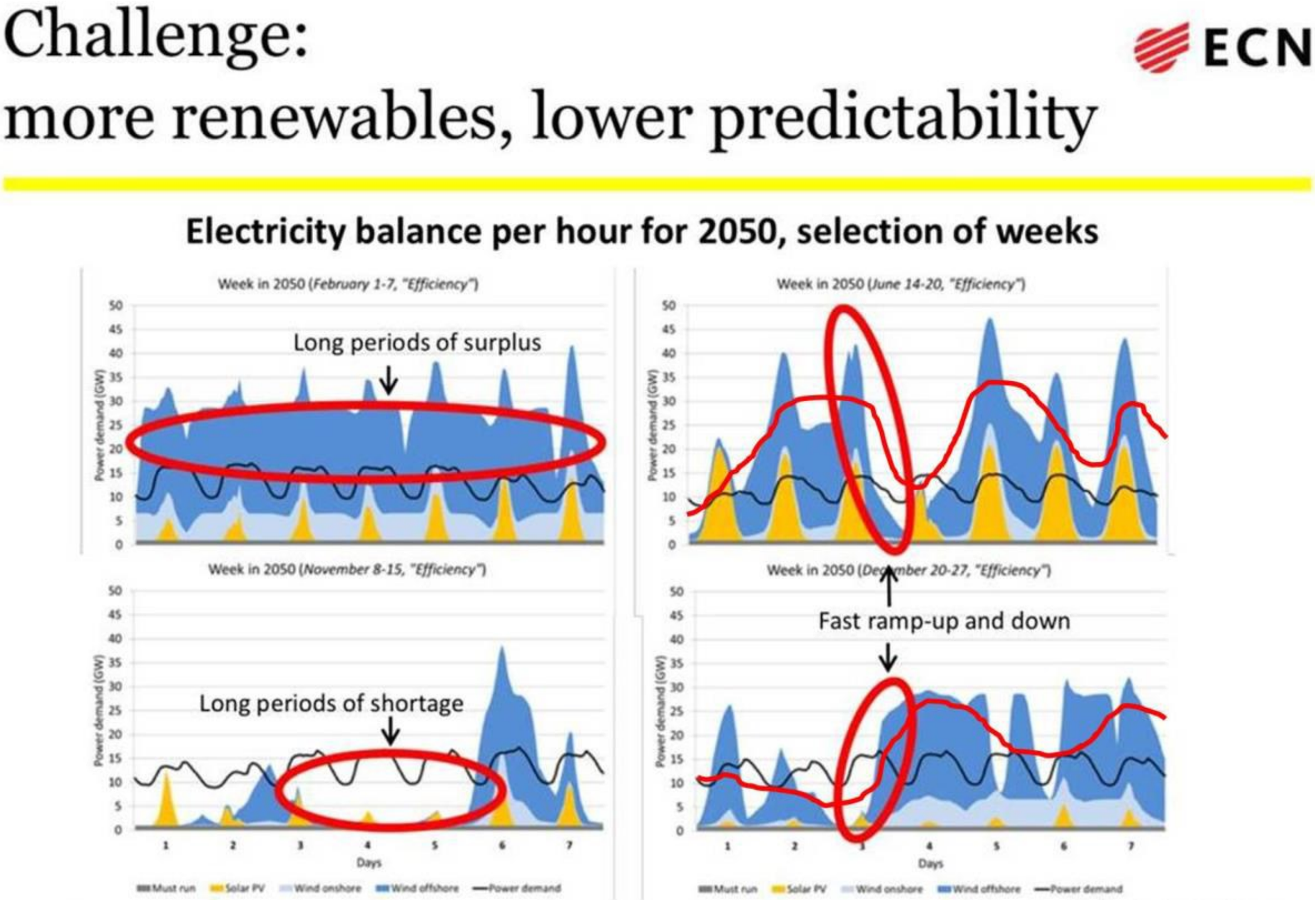
Due to the large part of vRES in the mix of energy sources at almost all times the demand will not match with the supply of energy: about 5000 hours per year the electricity production will be (much) higher than the demand and about 3700 hours the electricity production is (much) lower than the demand, as analysed in appendix C. So a series of flexibility measures has to applied to match demand and production.

Flexibility options are:

- demand response
- import/export. As we concentrate the system design from a regional view we only consider import much like a base load energy source.
- curtailment. In our scenario curtailment will be restricted to a quite low 2 TWh, only the highest excess energy production will be curtailed.
- long term energy storage: a backup system is required to produce the electricity demand in hours the produced energy is too low.
- short term energy storage for storing excess electricity in terms of hours to a day.

4.1 Short term energy storage: the advantages of a "One day storage system"

The diagram below illustrates some of the main challenges: long periods of surplus or shortage of energy and very fast changes in the supply (ramp-ups and ramp-downs). This can be seen in the diagrams below from (Ref. 18 Flexnet project ECN).



Challenge:
more renewables, lower predictability

Electricity balance per hour for 2050, selection of weeks

yellow = PV, light blue = wind onshore, dark blue = wind offshore, black = demand curve, red is curve with response including one-day storage.

Added to the original ECN diagrams (Ref. 18) is the expected result when PV and Wind energy are first passed through a one day storage system. It is shown by the two red curves in the two rightmost graphs. Those two red curves clearly show that the peaks in the supplied power can be very much reduced but even more important that , in periods where only a small amount of power is provided, the one day storage still provides significant power during those periods. This will result is less hours during the year where power from wind and PV is not enough to satisfy the demand.

As mentioned in the beginning it is expected that during a maximum period of one month not enough electricity will be generated by PV and wind. During those periods backup generators will be used to provide for the required electricity. There are two system issues that need to be addressed: the first one is how much backup power is needed, the second how much fuel (hydrogen or ammonia) is needed. To determine the required power one must look at the demand response possibilities of the different energy users in order to minimize the required backup power. We expect that especially the industry could scale back its energy use by reducing the output of the factory. Short term duration power limitations could be resolved by battery systems. They will be needed in any case to average out the output of PV panels for the duration of one day (and also the daily fluctuations in wind energy). We estimate that around 78 GW of PV panels will be needed for the total system. By using batteries for one day storage, the peak power of all the PV panels can be significantly reduced (to around 17 GW). It is in general also recommended to use the generated electricity directly at the place where it is generated without first sending the electricity to the network.

A one day battery system, strongly decentralized, is also useful to average the demand over one day in general because it is expected that less electricity will be used during the night than during the day.

From system studies and simulations (Ref. 9 P2G report ECN) it is shown that a one day battery storage system can reduce very significantly the variations of PV and wind power happening during a 24 hour duration. This reduces the need for curtailment but also reduces significantly the periods where PV and wind do not produce the required power and therefore also the amount of back up storage. This again reduces the amount of energy that will need to be generated by PV and wind. A one day battery storage system will not be cheap. In our design we propose a yearly energy production of PV and wind of 339 TWh. This results in an average daily energy production of 928 GWh. It is difficult to precisely define the needed amount of one day storage. We limit ourselves here to the amount needed to average the produced PV energy of 68 TWh. We should take into account the energy produced during the summer months. A 4 KW PV system will produce a peak of 3.5 KW on a sunny day. To average this over one day we estimate a needed capacity of 6 KWh. So for 78 GW PV we need about 115 GWh of one day storage. Note that this battery storage can also be used as a demand response function during not sunny days. A major part for this one day storage facility can be delivered with the battery systems of the fleet of electrical vehicles, supported by smart energy loading/delivering back systems.

So in summary , battery storage (one day duration) will play an important role, matching demand and variable production!

4.2 Backup power system: requirements and system aspects

As already described the system proposal will be based on a large 85% part of variable energy sources: wind and PV. Very often there is no match between energy production and demand. And in the hours the production is (much) less than the demand the backup system has to deliver the missing energy. The backup system is based on the production and storage of hydrogen by electrolysis during hours the total energy production is (much) higher than the demand. This stored H2 supply will be used during hours the energy production is too low: for the hydrogen demand for industry and transport and for the electricity demand via the fuel cell backup power plants, see the detailed block diagram in appendix A.

4.2.1 Backup power requirements

To analyse the backup requirements enabling the delivering of the energy in the hours with too less energy production the power duration curve of the variable electricity production is a very useful tool. A clear example for such duration curve is presented in the Power to Gas Study from ECN, ref.9 and matches reasonably with the analysis of our energy system. In appendix C, figure C3 our analysis based on this power duration curve enables us to get a good overview of different important figures:

- about 5000 hours the energy production is (much) higher than the demand; during those hours the excess electricity will be converted to hydrogen via electrolysis and stored to be used during hours, the energy production is lower than the demand,
- about 3750 hours the energy production is (much) lower than the demand
- about 30 TWh electricity for the H2 demand has to be delivered from the stored H2
- about 960 hours per year the direct electricity demand has to be delivered partly from the backup system: a low 10 TWh! For safety reasons we introduce a save 12 TWh as the output of the backup system in an average year.

4.2.2 Annual PV and wind electricity fluctuations.

A last comment is about the varying yearly production of PV and Wind. In our design that is a total of 339 TWh. But that is an average figure. In some years it will be more, in other years it will be less. It is important to examine the yearly fluctuations of this supply. We have analyzed the data from Ref 7 and Ref 21 as well the production data of the London Array with 630 MW. From those data we can conclude that in the years with a minimum production of energy, this energy will be about 6 percent lower than the average production. Choosing a save
10% as the ultimate limit, the variable energy production will miss in a bad year, 30 TWh. An acceptable way to deal with annual fluctuations is to adapt the yearly imported electricity.

4.2.3 Some system aspects

The conversion from electricity to hydrogen will produce quite some heat. This heat should not be wasted. The conversion of electricity to such a fuel will require electrolyzers and they can be operational during most of the year. Therefore it is good to locate those electrolyzers close to heat users because heat cannot be transported over long distances. One suitable location can be close to city heat networks. Another aspect is the question how and where to generate the backup power. Nowadays this is done by large gas turbines or WKO’s.

In the further future fuel cells will be manufactured in large quantities and their performance will also increase in terms of efficiency, the KW’s per unit volume and also in terms of their lifetime. Therefore we recommend that the backup power system be implemented as fuel cell power stations. It is claimed by some people that fuel cell plants will be less expensive than gas fired turbine plants in the future.
Also the fuel cell power plants will produce heat during the electricity production but that will be done during only one month a year. It is not sure if one should try to use that heat because its production moment and amount cannot is difficult to predict. A part of this hydrogen fuel cell backup system can also be formed in future by the many hydrogen fuel cell transport electric vehicles.

The generation of backup electricity will be distributed over the year and not be concentrated in the winter or summer period. The fact that during only about 960 hours per year back up electricity will be needed has several consequences.

The first is that of the influence on the acceptable KWh price for backup electricity. It is foreseen that PV and wind power can be produced at around 5 cents per KWh (see Ref. 22). This is the production cost, not the cost at delivery. If we indicate the cost of backup electricity as CostBE then the average yearly price of one KWh will be (11*5 + 1*CostBE)/12 . From this it can be seen that CostBE may be rather high with little effect on the yearly price.

The second is the maintenance and life time of the backup power system. For several reasons, which we will elaborate on later, we prefer a distributed backup system consisting of fuel cells. It is documented that fuel cells have a rather limited lifetime. But because they will be used for only one month a year, their lifetime will be extended significantly.

5. Power generation requirements

In section 3.1 the mix of renewable energy sources are discussed. Wind and PV energy have a large 85% share in this mix. Some remarks could be made about these very variable sources.

a. Wind at sea at 256 TWh/63 GW

We expect to need 60 GW of wind power at sea. But is that achievable? Many studies consider the North sea as in import source for renewable energy able to produce a large part of the desired green energy of the North Sea countries. But the sea is also a very busy sea, occupied by a large number of other users: shipping, fishing, cabling and piping, nature reservation etc. This will restrict the possibilities for developing wind parks. But a large area will still be available for wind energy. Especially the area around the Dogger Bank offers large possibilities for wind energy. A key parameter is the average power per square km. Older studies mention average numbers as 2 MW/km2, but latest studies shows average numbers from 6 to 9 MW/km2. See ref 17, 19 and 19a.

Important are the studies of TenneT to facilitate the large scale wind power development of the Dogger Bank with one or more energy islands able to facilitate the energy exchange between the 6 North Sea countries with 30 GW for each island, see ref. 22.

So with the modern turbines, 10-15 MW and with 4500-5000 full hours per year, we may expect that anno 2050 an average wind park power density of 7 MW/km2 is well possible with a park efficiency of around 85%. So the required 63 GW wind power requires 9000 km2net sea area. With the Dutch part of the North Sea being 57.000 km2, the required wind energy requires about 16% of the total sea area.

How many wind parks will be needed, how large they should be and where they should be located, is an important study, but not subject of this study. Nevertheless we can state that the wind parks are better equally distributed over the entire Dutch part of the North Sea in order to avoid mutual interference between them. It is anticipated however that by 2050 the allocation of several functions currently assigned in the North Sea may be changed considerably by then.

Electricity transport from the Dogger Bank to the Dutch coast
Considering the good wind conditions of the large Dogger Bank area we may expect the construction of wind parks with 40 GW in total or even more on the Dutch part of the Dogger Bank! The other 20 GW will be delivered by wind parks much closer to the mainland with cable connections for the electricity transport to mainland.

But the distance from the Dogger Bank is much larger, about 250 km. The electricity transport to land via cabling will be rather expensive. An alternative energy transport, based on the on-sea electricity conversion to Hydrogen with on-sea electrolysis and transported by pipelines (already partly available) may be a more economical solution. A possible implementation may be to transport electricity with a maximum power capacity supported by the power cables. The 40 GW wind park could be connected to the Netherlands by for example a 10 GW connection. This connection could carry electricity with a power close 10 GW for a large part of the year.

b. Wind on land 15 TWh/6 GW

This is a realizable solution for the Netherlands and takes into account that we have a densely-populated country with limited options for locating wind turbines. Social acceptance plays an important role and 6 GW seems to be the upper limit.

c. PV panels at 66 TWh/78 GW

Is this a reasonable possibility for 2050?
It probably is, considering the expected efficiency of solar panels in 2050 and the available area on buildings and rooftops, along infrastructures (like railroads and high ways) and solar parks.

d. Role of curtailment

Curtailment is sometimes unavoidable in hours of high sun and strong winds. But it also offers a possibility to avoid these highest power peaks to feed the electrolyze systems. In that way the total maximal power requirement for the electrolyzes can be lowered.

6. System stability and controllability and import/export strategy

It is important that the system will be a stable system and that the required power can always be delivered, with the same reliability as it is nowadays. To make the system more stable and also better controllable we suggest using a large one day storage facility, which will be mainly distributed. This was mentioned already above to average out the peak currents from the PV panels, but it can also be useful to average out wind power as well as large variations in the power consumption.

Although we focus on a regional view, we are still aware that an import/export strategy offers an important flexibility option: exporting excess energy and importing in hours the own production is too low for the demand. Nowadays we already have good power connections with the neighboring countries. And coming decennia the European network will be strongly expanded, enabling electricity exchange Europe wide. Also the idea from TenneT to develop one or more energy islands around the Dogger Bank aims to use the energy from the planned wind parks on the Dogger Bank in an optimal way between the six North Sea countries. For instance a European wide view will lower the need to have available a large own strategic storage of H2 (or possibly NH3) as was discussed at end of section 4.2.

But still some remarks about import/export strategy may be made.

Export can always be done when there is an excess of energy. The issue is more on the role of import. Import can be done for two different reasons.

The first one is because on a yearly basis we generate less energy than what we need. Import of energy for this reason should be seriously considered mainly because the Netherlands is very densely populated. When this energy is imported at moments that there is sufficient electricity available in neighboring countries, the price of this electricity can be very attractive.

The second reason could be to compensate for (short) periods when the local production by wind and PV is not sufficient to provide for a minimal required power. This raises several practical problems. There is a limit to the rate of change of the supplied power from other countries (defined in GWatts/hour). The first problem is that power generation capacity in other countries must be able to ramp up and ramp down at a very high rate. One may also expect that the energy price for such import will be very high. The second problem is that the electrical transport lines must be able to handle high peak currents. It is much better to first average the internal demand , either by demand response or by using battery storage and also a fast response backup system.

7. The implications on the location of the interconnect and conversion systems

We mentioned above already one issue that has to do with the use of heat as a result of the conversion of electricity in an energy fuel. There is another issue concerning the generation and transport of the energy fuel. We estimate that around 60 GW will be needed for wind at sea but the question is whether the generated electricity can best be transported with costly electric cables in the North Sea. Maybe it is better to generate a large amount of the needed energy fuel (hydrogen or ammonia) on the energy island, close to the wind turbines, and transport this to the shore by ship or a pipeline.

Another issue has to do with the foreseen transport system. To enable this it will be needed to make energy fuel stations available at sufficient places, probably best to start on all highways. Those filling stations could also generate the needed energy fuel at their location making use of periods when there is cheap electricity available. Those stations should have storage tanks that probably are sufficient to cover the need for one or two weeks. Such stations already exist in Germany.

The placement of the decentralized one day energy system as a distributed system could also help to reduce the required amount of electrical network capacity since peak currents will be reduced to a large extent.

8. Conclusion

A carbon free energy system is possible in the future and this study provides details on how it can be realized. A detailed system simulation is needed however to fine tune the different parameters of such a system.

9. Main sources of input for the design study

1. EU-2050 powerlab:
    - https://www.kivi.nl/eu2050powerlab

2. Homelab2050:
    - https://www.kivi.nl/homelab2050

3. EnergyNL2050:
    - https://www.kivi.nl/energynl2050

4. Advice from the Rli to the Dutch government:
    - http://www.rli.nl/publicaties/2015/advies/rijk-zonder-co2-naar-een-duurzame-energievoorziening-in-2050

5. CE Delft 2015 “Verkenning functionele energievraag en CO2 emissie tot 2050”:
    - http://www.rli.nl/sites/default/files/verkenning_functionele_energievraag_en_co2emissies_in_2050_-_ce_delft.pdf
    - http://www.ce.nl/publicatie/verkenning_functionele_energievraag_en_co2-emissies_tot_2050/1716

6. Fraunhofer report about ratio PV wind

7. Fraunhofer 2010 : 2050 100 percent : energy target 100 % renewable electricity target

8. ECN report about windfarms

9. ECN Power to GasPower2 final report (figure 7 power duration curve)
    - https://www.ecn.nl/docs/library/report/2014/e14026.pdf

10. Umwelt Bundesamt/Fraunhofer, 2014 “Treibhausgasneutrales Deutschland 2050”.

11. Fraunhofer ISE, 2015.”Recent facts about Photovoltaics in Germany”, fig 55,

12. TNO, Dr Martijn de Graaff, KIVI EnergyNL2050 presentatie 22/11/2016
    “Electrification of Chemistry”

13. CE, Ir Frans Rooijers, KIVI EnergyNL2050 presentatie 13/10/2016
    “EnergyNL2050, klimaat neutraal energiesysteem”

14. http://nhthree.com/ssas.html, sept 2014

15. Dr Remco Ybema, KIVI energyNL2050, presentatie Utrecht, 22/11/2016
    Sustainability approach of AkzoNobel.

16. Dr Marcel Weeda, et al, ECN, Power-to-Gas, missing link in toekomstige energie voorziening, 20/6/2013

17. P.J.H Volker and other 2017 : “Prospects for generating electricity by large onshore and offshore wind farms”, Environmental Research Letters issue 12 (2017)

18. FLEXNET project ECN 2017

19. ECN report on Potential yield of Windfarms – 2016

20. B. Bulder at all: Quick scan wind farm efficiencies of the Borssele location, 2014, ECN B. Bulder at all.)

21. Presentation of Hans Kiesewetter on November 22, 2016 (see weblink in Ref 3)

22. Danish wind production data. www.ens.dk

23. Alan Croes, TenneT: Future North Sea (Wind Energy) infra structure.
February 9, 2017 KIVI energyNL2050 symposium

24. HyUnder studies: H2 storage in salt cavernes, M. Weeda, J. de Joode,
ECN Solar-PV 2050 Power Lab KIVI- seminar, April 24, 2014

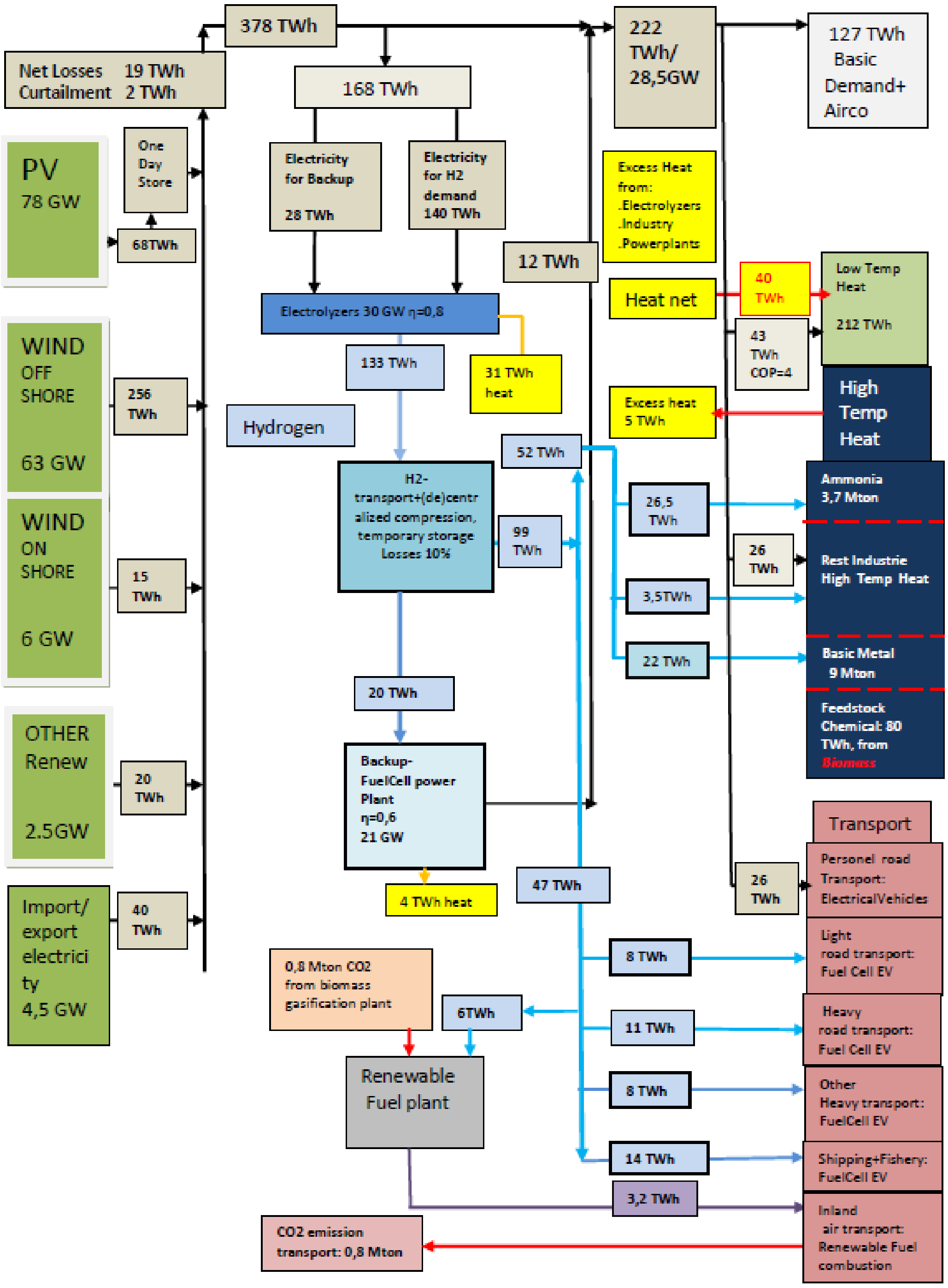
25. “CO2 emission free iron making” LKAB/Vattenvals, April 2016

26. “Solar to the People”, prof. Ad van Wijk, November 2017

Appendix A: detailed system diagram

Zero - CO2 - Scenario:

Annual primary energy demand: 399 TWh full electric;
CO2-emission: 0 (0,8) Mton;



Summer and Winter demand and production in balance. CO2 re-use for renewable fuel production from biomass gasification

Appendix B: Distribution of the demand over the year

For a realistic energy system design 2050 it is important, between many other things, that good annual profiles for the different renewable energy sources and the different demand sectors are used. It enables us to get good results for possible excess electricity, produced in summer or winter. It even makes possible to derive an optimal ratio between the produced Wind-electricity and PV-electricity, minimizing the summer or winter excess electricity to zero! For a first order calculation, resulting with such an optimal ratio, we need at least a good division for the summer part (April-September) and the winter part (October- March). Using some other studies, see added figure from Fraunhofer ISE (www.ise.fraunhofer.de) as an example, the following summer/winter divisions could be obtained in terms of percentages:

Energy demand	**Summer**	**Winter**
High Temperature heat	50%	50%
Low Temperature heat	20%	80%
Transport	50%	50%
Basic Electricity + Airco	50%	50%

Energy supply	**Summer**	**Winter**
Wind	40%	60%
PV	70%	30%
Other Res	50%	50%
Import electricity	50%	50%

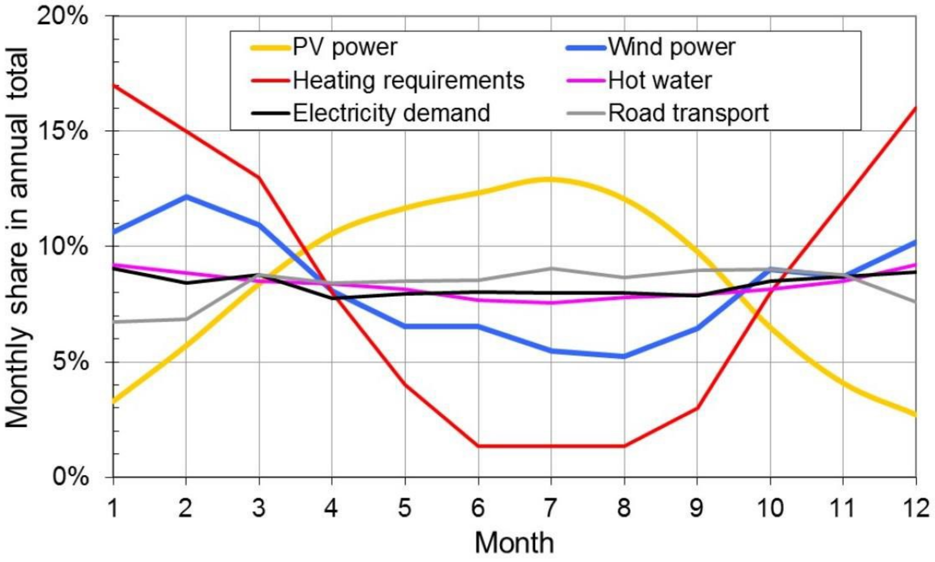


Figure 46: Rough estimate of the monthly distribution (annual total = 100 percent) of solar power calculated for Freiburg [PVGIS], wind power [DEWI], heating requirements based on the heating degree days (VDI Guideline 2067 and DIN 4713), energy requirements for domestic hot water production, electricity demand [AGEB1] and fuel requirements [MWV].

Figure from Fraunhofer/ISE, 2017: "Recent Facts about Photovoltaics in Germany", fig. 46

The numbers can be well understood: much PV-electricity in summer and more Wind-electricity in winter. Also the Low Temperature Heat demand will be much higher in winter. Analysing the energy system with these numbers, but as a first step a equal division of the demand sectors, the optimal ratio for the Wind-electricity/ PV-electricity is 2, resulting in a zero seasonal based excess electricity. But due the actual greater heat demand in the winter, more electricity in winter than summer will be required, resulting in a shift to more wind-electricity. As a result from this analysis, using the summer/winter division as above, the optimal ratio Wind-electricity/ PV-electricity will become about 4, meaning that the summer or winter excess electricity will be zero!

Appendix C: Estimation of the required backup capacity with the aid of the power duration curve of the variable energy sources wind and PV electricity.

The figure C1 is a picture from the P2G study from ECN, see ref 9. This picture shows a curve of the power produced by the variable renewable energy sources (vRE) Wind-electricity and PV-electricity during the year. It has been constructed with 16 time slices, varying in length from some hours up to more than 1000 hours. In each time slice the hourly vRE values are averaged over de length of the time slice, as a result from their extensive analysis. The 16 time slices are ordered along the hour axis approximately with decreasing value of vRE, but not exactly. This is due to the fact that in ordering the time slices along the hours axis, the demand in the time slice hours has played a role too. This means that we may not consider the curve as a correct power duration curve, only as an approximation. We made that approximation by substituting the curve with a linearized contour curve as depicted in figure C2.

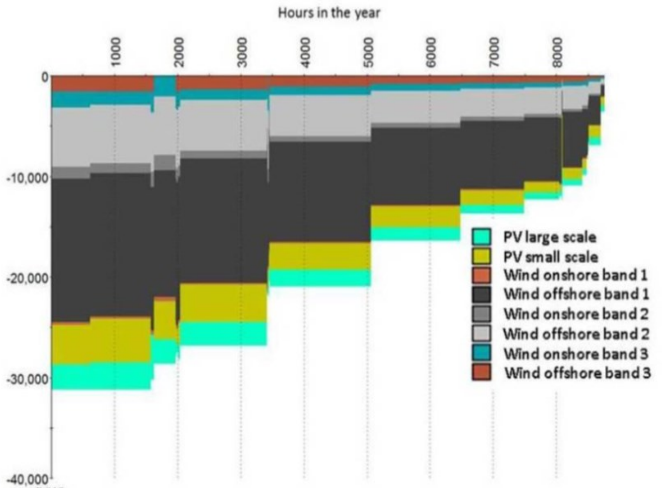


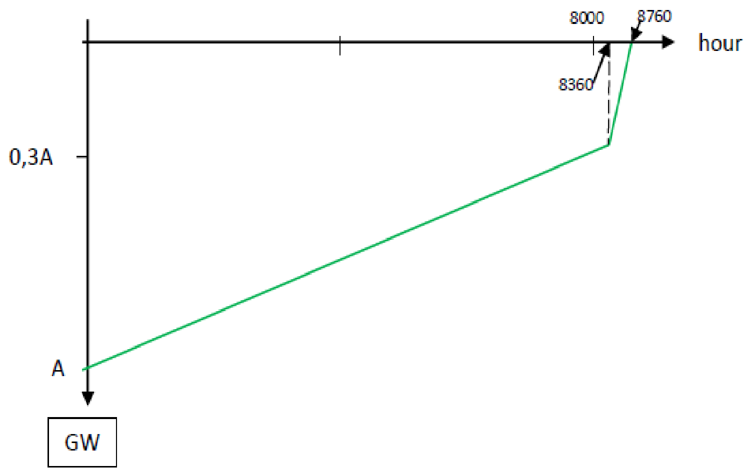
Figure C1 . Published curve by ECN

The ratio of the Wind/PV-electricity is about 4, the same as in our study (important to avoid summer or winter excess electricity!)

Be aware that the hour numbers on the time axis are not in a normal time sequence.

A real duration curve is an important analysis tool, enabling us to analyse the necessary backup demands. We made our own study and analysis of how a PDC could look like, considering a mix of renewable energy source dominated by the offshore wind parks. With more than 60 GW offshore wind energy defined, the offshore wind parks are widely distributed across the Dutch North Sea part, from Borsselle along the coast of North and South Holland to the Wadden and up to the Doggersbank. We may conclude that in most of the hours a number of varying wind parks are generating electricity.

We came to the conclusion that such a PDC will have a shape quite comparable to the shape of the figure above. It is important to mention however that it is needed to perform new computations to establish the PDC conform our system proposal, including measurements of weather information on a sufficient amount of measurement locations.



So both discussions lead us to a power duration curve for our design in a general restyled curve as depicted in figure C2. This power duration curve is composed of 2 straight lines. Important is the observation, that the number of hours with low or zero vRES is small, about 400 h per year (at the right side of the graphic), as a result of the large part, the wind-energy as one of the components of vRES.

Figure C2: generalized and restyled duration curve for a situation Wind/PV energy ratio is about 4 . With aid of the values in the block diagram this generalized restyled duration curve can be actualized to the actual power duration curve, shown in fig. C3 at the negative side of the power axis.

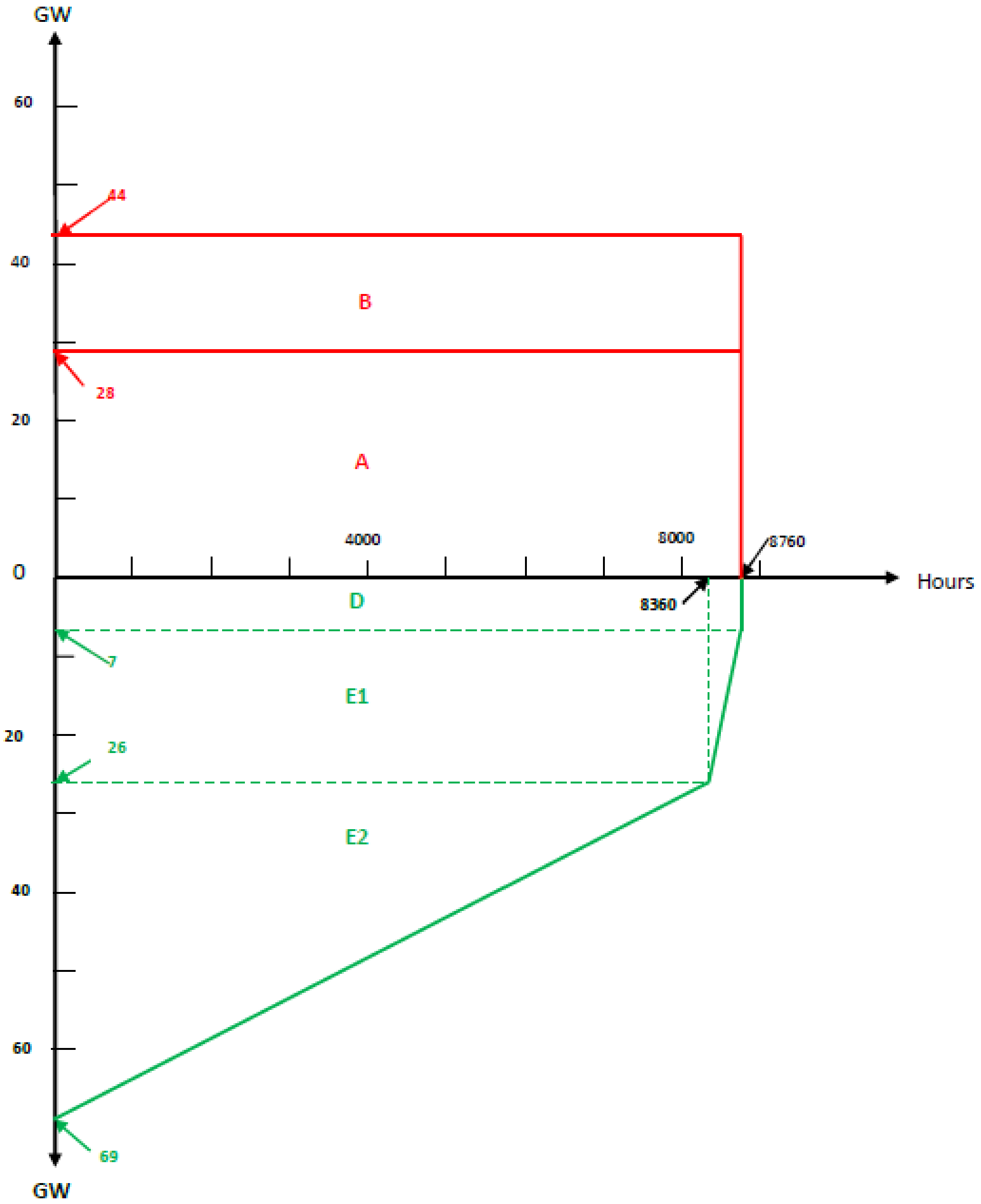


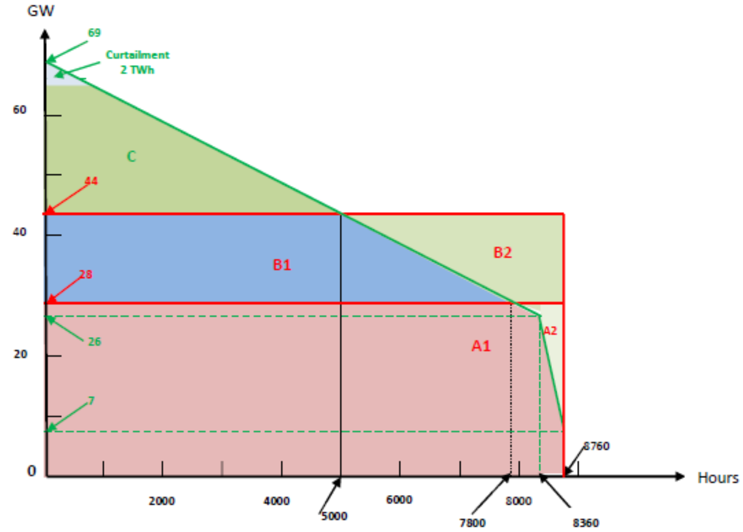
Fig. C3 Actualized Power duration curves, on the negative side of the Power axis the total production; on the positive side the total demand: electricity and H2 plus net losses and backup conversion losses.

To this curve we add the contribution of 20 TWh (from other renewable) and 40 TWh (from import) resulting in a total power contribution of 7 GW during the entire year, supposing that both energy sources are about constant during the year. The area D covers 60 TWh from the two latest sources and E1+E2 covers the total variable energy from wind and PV: 339 TWh. In total 396 TWh are produced by the renewable sources.

As a second step the total demands on electricity for direct electricity demand and for the H2 demand (heat HT and transport) can also be shown in this figure at the positive side of the power axis of the figure, see the red lines in fig. C3. As a first approach the demands are supposed to be about constant during the year and can be depicted as straight horizontal lines. The power levels of these demands correspondent with the values in the annual block diagram.

The area A covers the total direct electricity demand from the block diagram's right side plus the net losses: 222+19=241 TWh. The area B covers the total electricity 140 TWh required to generate the H2 demand for industry and transport.

The figure C3 may be considered to be an energy balance diagram, but just on an annual base. It is clear from the figure that a large number of hours the production is (much) higher than the demand, and also a large number of hours the production (much) lower than the demand. To get more insight in these observations, mapping of the energy production lines from the negative diagram side to the positive side in the figure C3 gives a much better view about these points and will learn some important information for the system design.
See figure C4.



From this figure C4 we can see, that about 5000 hours a year the energy production is higher than the demand. This is the dark green triangle area C covering about 58TWh, including the 2 TWh curtailment. This excess electricity has to be converted in H2 and temporarily stored to be used for backup demands.

Area B covers the 140 TWh electricity demand for the production of the H2 demand for industry and transport, but only the blue area B1 indicates the hours that the electricity sources are able to deliver the H2 demand electricity directly; the green area B2 covers the hours the electricity sources cannot deliver the required electricity and the H2 demand must be delivered via the stored H2 produced by the excess electricity from area C.

Area B2 covers about 30 TWh.

Area A=A1+A2 covers the total direct electricity demand plus the net losses, in total 241 TWh. The red part A1 is fully covered with hours, the electricity sources produce enough electricity. Only the small light green part A2 is not covered by the energy sources and has to be delivered from the backup Fuel cell Power Plants. This A2 part is about a low 10 TWh during about 960 hours per year. In our system design we therefore introduced a save 12 TWh backup electricity, a bit more than this theoretical 10 TWh as the output from the backup power plant. Be aware that the production of this 12 TWh backup electricity needs 28 TWh as can be seen in the block diagram with the backup system losses are 16 TWh.

So in total the backup energy, delivered from part C should be 30+10+16=56 TWh.

Conclusions from this study are:

- Applying the restyled actualized power duration curve as a system design tool gives important information:
- Required backup electricity is about 10 TWh (in our system design is fixed to 12 TWh),
- For the H2 demand for Industry and Transport 30 TWh H2 has to be generated and temporarily stored from the excess electricity when energy production is higher than the demand.
- The excess electricity during about 5000 hours per year is 58 TWh. 2 TWh is necessary for inevitable curtailment; 56 TWh is converted in hydrogen and temporarily stored for demand applications.

The Dutch energy system will look quite different in 2050 from what we have now. It is very important to have a detailed view on the expected 2050 system so that an efficient transition can be defined and realized. Many published scenarios still make use of a considerable amount of carbon fuels in 2050 which makes it difficult to arrive at the desired CO2 emission targets. It is often claimed that this cannot be achieved without the (extensive) use of CSS technology.

We have set as our goal to have a zero carbon energy system and investigate if the Netherlands can satisfy the demand largely by energy resources from the Netherlands. This design study shows that this is indeed possible. However it will necessitate big changes in how we use energy at the demand side and how we match the demand with the available energy supply. The proposed design has not been simulated but seems feasible. Nevertheless it is suggested to perform simulations in order to validate the design.