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The future Dutch full carbon-free energy system

Results of the KIVI–EL Renewable energy study group

A design study of

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Summary

The Dutch energy system will look quite different in 2050 from what we have today. 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.

Introduction

The intent of this paper is to analyze 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 CO_2 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)

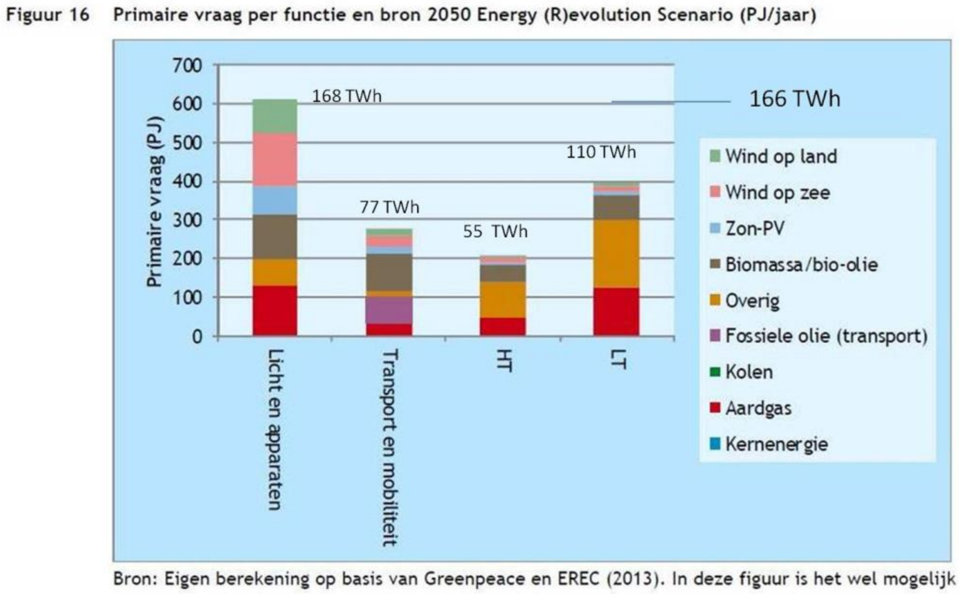


Figure 1: Energy demand according to Greenpeace R scenario

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 electrolyzers (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 electrolyzers, 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 electrolyzers 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 CO_2 emission: the ammonia industry with about 2 Mton CO_2 per Mton ammonia produced and the production of basic steel also with an emission of 2 Mton CO_2 or more per Mton basic steel.

. The ammonia production is based on the synthesis of N_2 with H_2. The hydrogen is produced nowadays by methane with a steam reforming process, responsible for the large CO_2 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 CO_2 emission. For the transfer to a green process with zero CO_2 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 "CO_2 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 CO_2 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 CO_2 emission from air transport is unavoidable. But when the fuel will be produced via synthesis of green Hydrogen with captured CO_2 from air (or from seawater!) or from a CO_2 point source the transport function may be considered as carbon free!
In our scenario proposal the CO_2 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 CO_2 (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 CO_2 emission of 40 Mton CO_2.

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 H_2 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 H_2 demand is 140 TWh.

The H2-fuel cell backup system, delivering 12 TWh_{el} annually , as described in part 4, requires another 28 TWh electricity for electrolysis. The electrolyzer 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 <u>primary</u> 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 TWh_{el} 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:

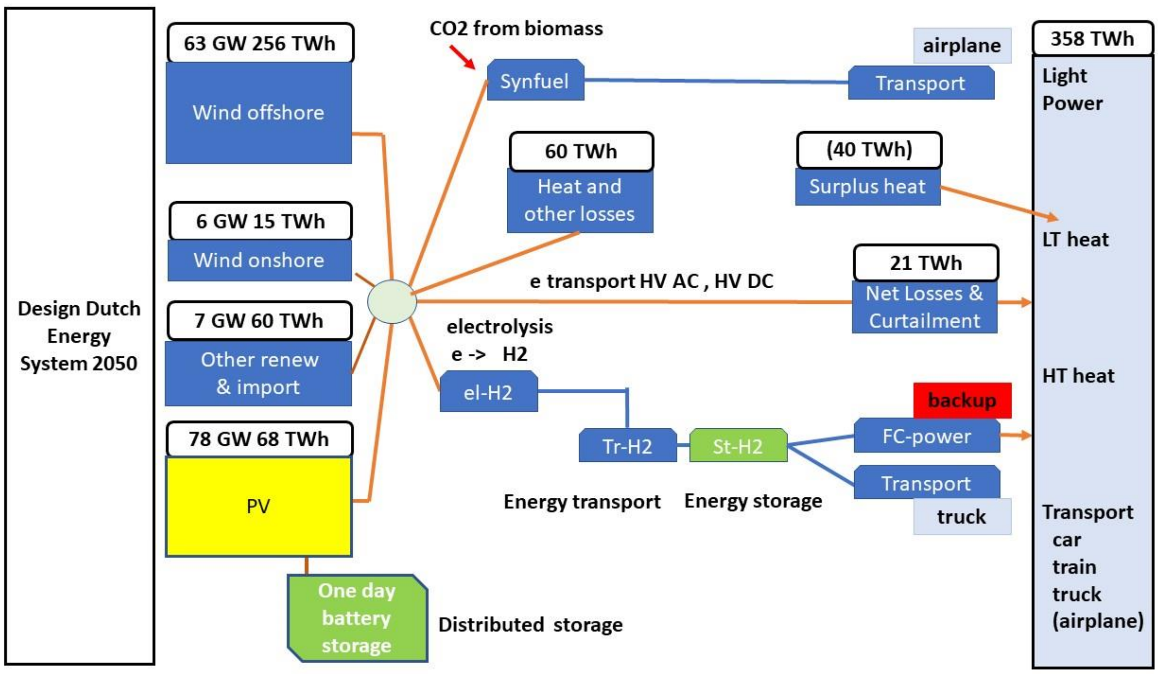


Fig 2. Simplified block diagram of the energy system NL2050. Total primary energy usage is 399 TWh. See diagram in appendix A for more details.

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 analyzed , 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 analyze 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 analyzed. 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).

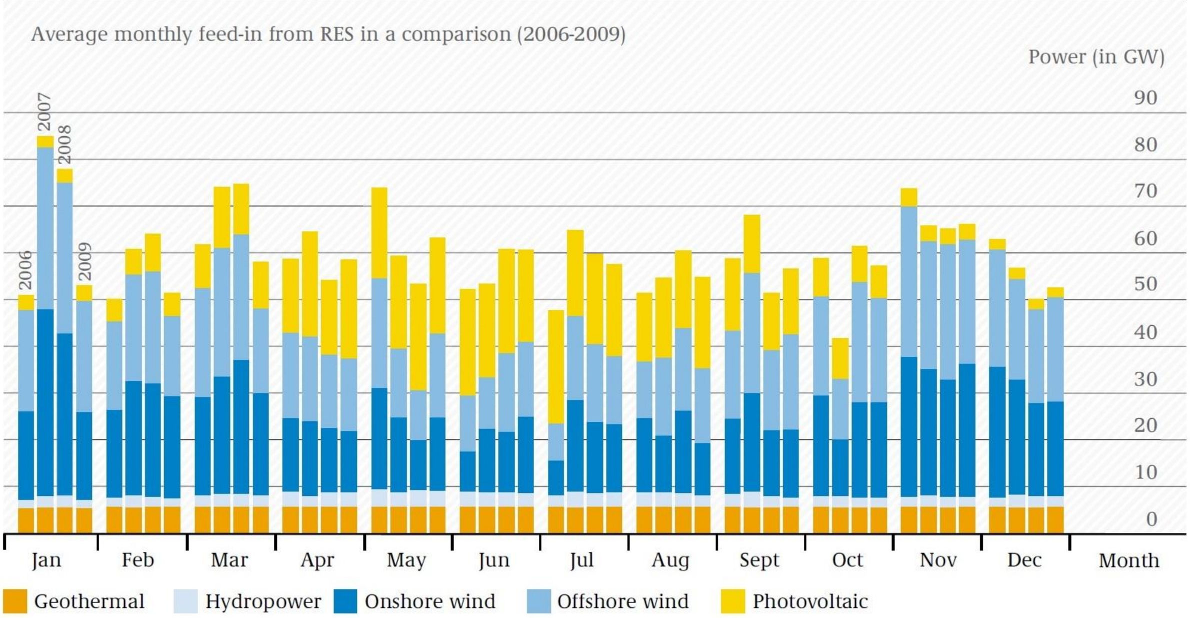


Figure 3: from reference 7

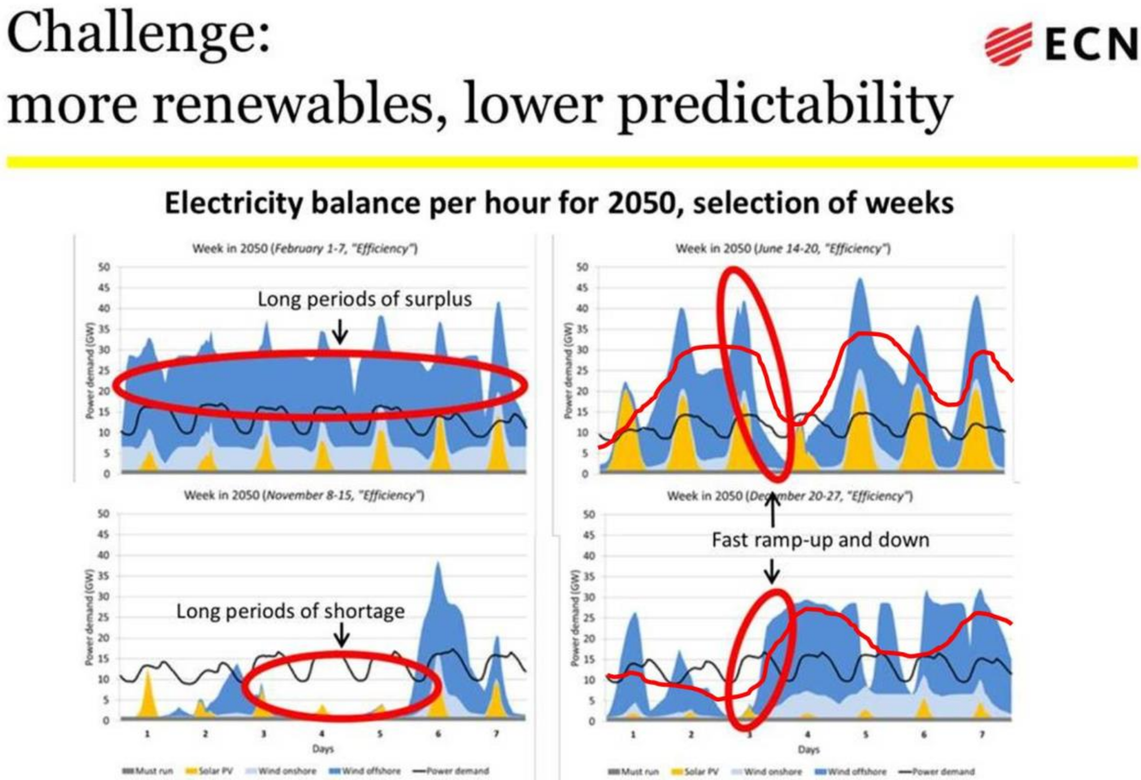
The above figure comes from the German report (Ref. 7) and shows how Wind and PV energy complement each other quite well. For clarity, we will not use Geothermal or Hydropower in our system proposal.
Designing the system with minimal seasonal excess electricity is strongly preferable, because it minimizes 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 analyzed 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 on a 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).



yellow = PV, light blue = wind onshore, dark blue = wind offshore, black = demand curve,
the red curve is the 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!

4.2Backup 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 analyze 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/km^2, but latest studies shows average numbers from 6 to 9 MW/km^2. 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/km^2 is well possible with a park efficiency of around 85%. So the required 63 GW wind power requires 9000 km^{2}net sea area. With the Dutch part of the North Sea being 57.000 km^2, 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 an 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 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

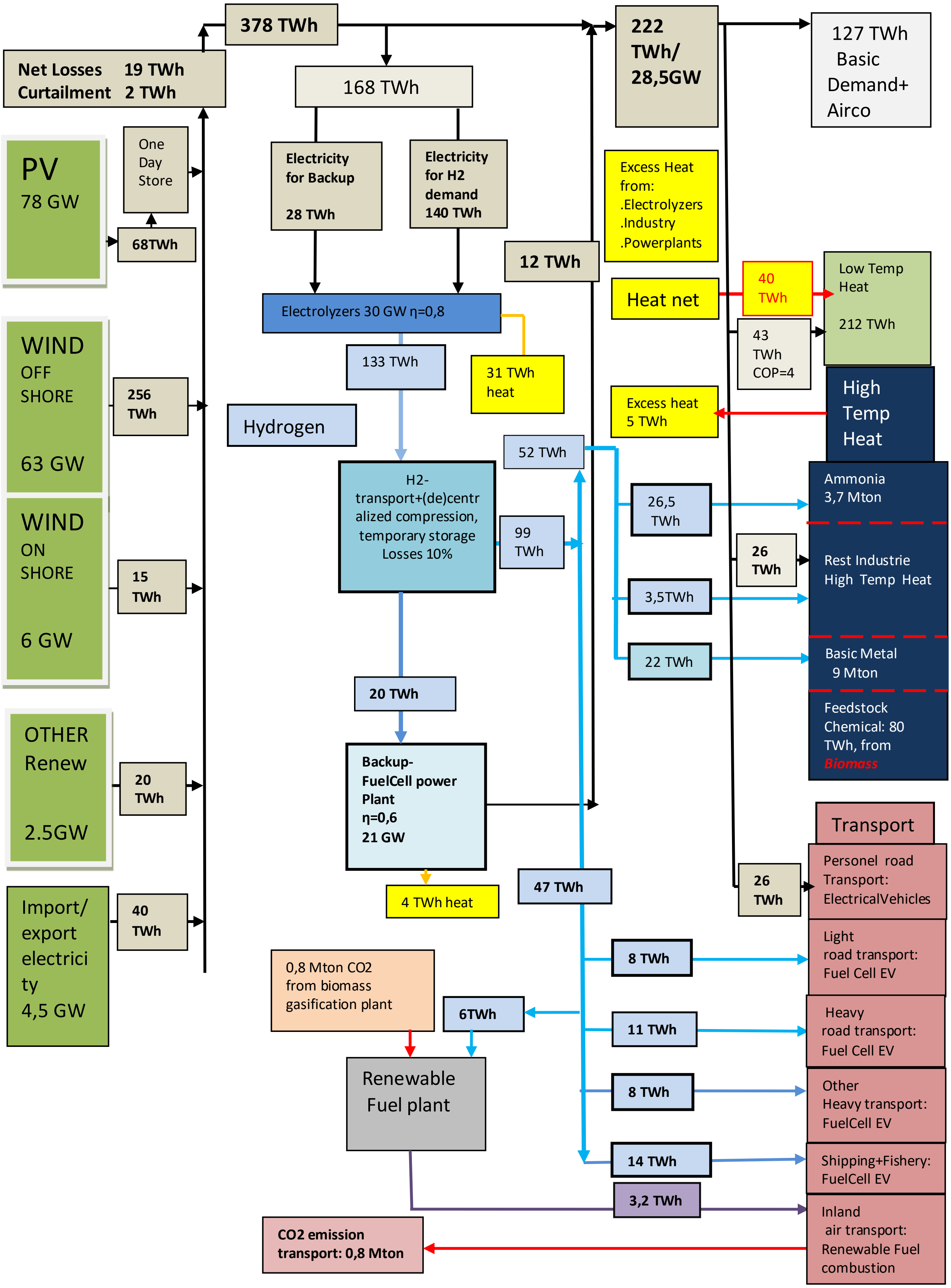
1. EU-2050 powerlab https://www.kivi.nl/eu2050powerlab
2. Homelab2050 https://www.kivi.nl/homelab2050
3. EnergyNL2050 https://www.kivi.nl/energynl2050
4. Advice from the Rli to the Dutch government
http://www.rli.nl/publicaties/2015/advies/rijk-zonder-co2-naar-een-duurzame-energievoorziening-in-2050
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 presentation 22/11/2016
“Electrification of Chemistry”
13. CE, Ir Frans Rooijers, KIVI EnergyNL2050 presentation 13/10/2016
“EnergyNL2050, klimaat neutraal energiesysteem”
14. http://nhthree.com/ssas.html, sept 2014
15. Dr Remco Ybema, KIVI energyNL2050, presentation 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
19a. B. Bulder at all: Quick scan wind farm efficiencies of the Borssele location, 2014, ECN B. Bulder at all.)
20. Presentation of Hans Kiesewetter on November 22, 2016 (see weblink in Ref 3)
21. Danish wind production data . www.ens.dk
22. Alan Croes, TenneT: Future North Sea (Wind Energy) infra structure. February 9, 2017 KIVI energyNL2050 symposium
23. HyUnder studies: H2 storage in salt cavernes, M. Weeda, J. de Joode, ECN Solar-PV 2050 Power Lab KIVI- seminar, April 24, 2014
24. "CO2 emission free iron making" LKAB/Vattenvals, April 2016
25. "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;
CO_2-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%

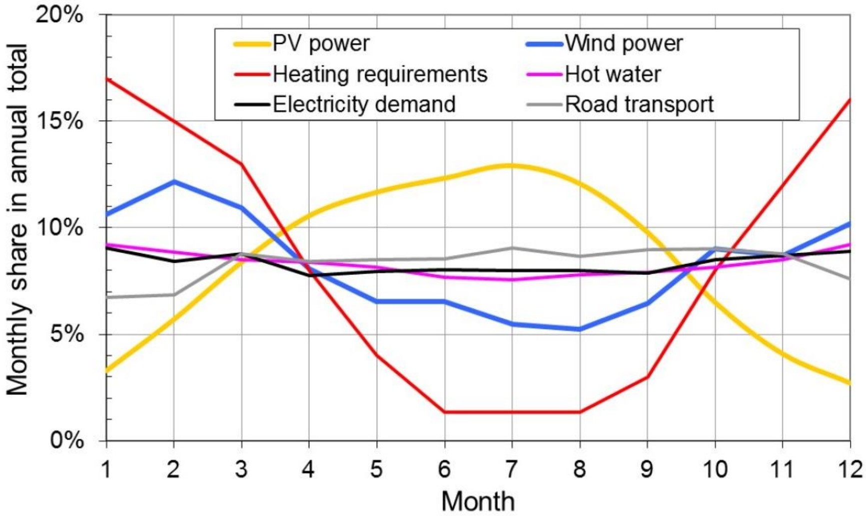


Figure 46: Rough estimate of the monthly distribution (annual total = 100 percent) of solar power calculated for Freiburg [PVGIS], wind power [DEWI], heating requirements based on the heating degree days (VDI Guideline 2067 and DIN 4713), energy requirements for domestic hot water production, electricity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

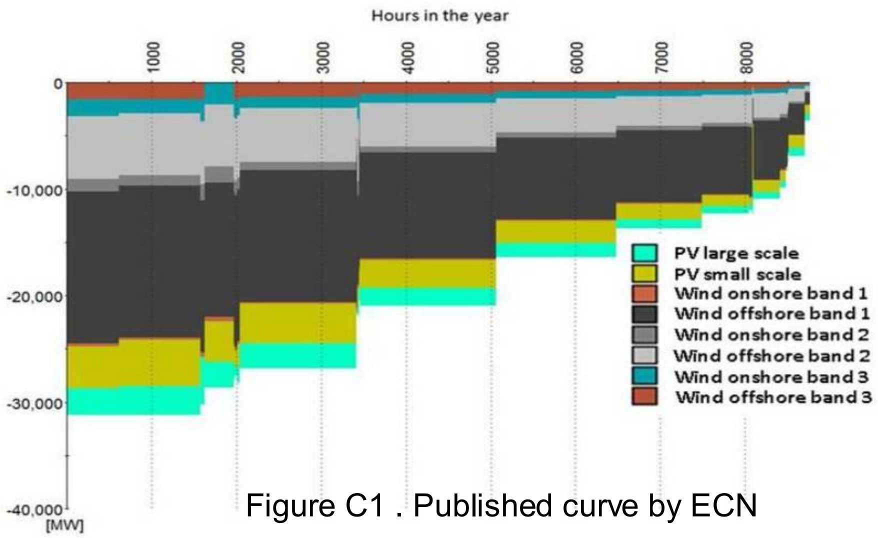


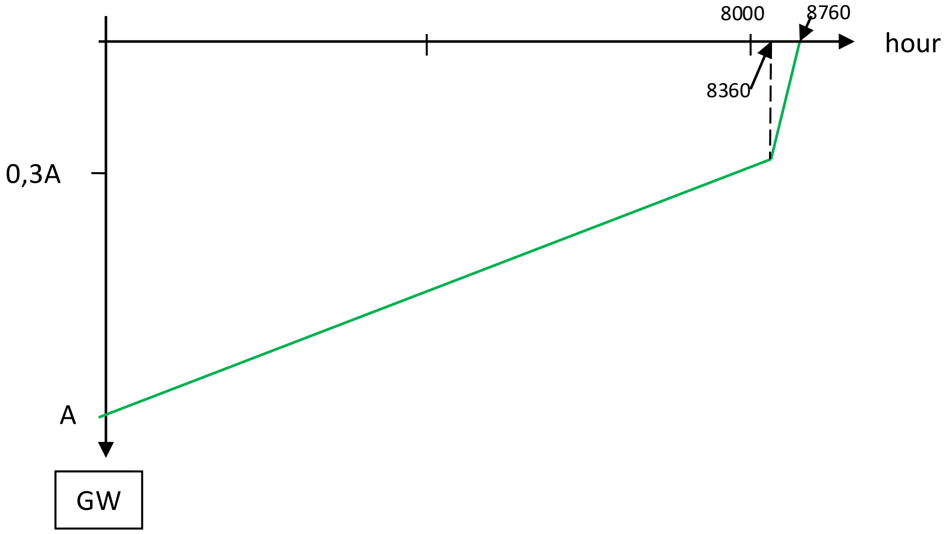
Figure C1 . Published curve by ECN

A real duration curve is an important analysis tool, enabling us to analyze 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 Borssele along the coast of North and South Holland to the Wadden and up to the Dogger bank. 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.

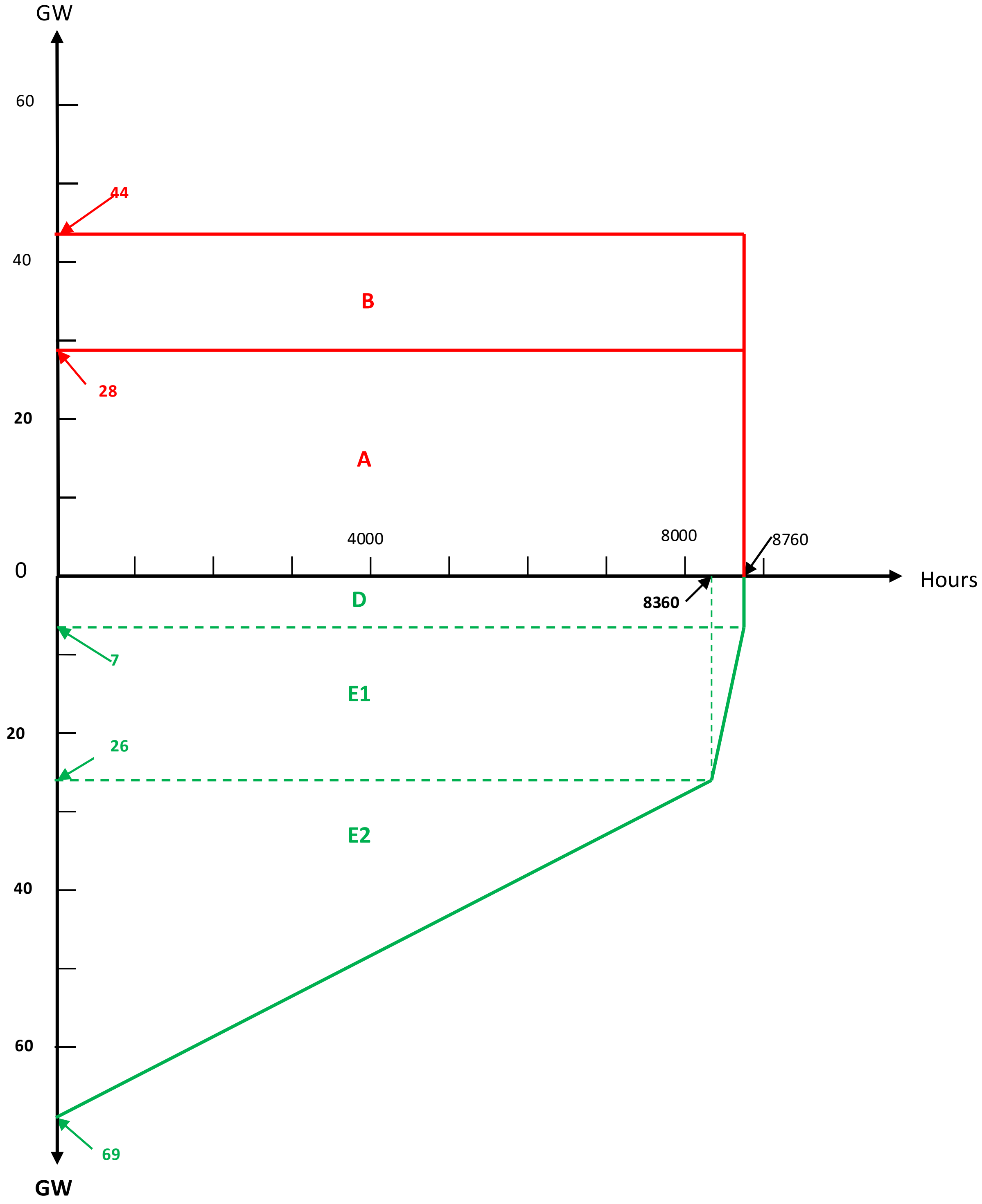


Fig. C3 Actualized Power duration curves, on the negative side of the Power axis the total production; on the positive side the total demand: electricity and H2 plus net losses and backup conversion losses

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.**

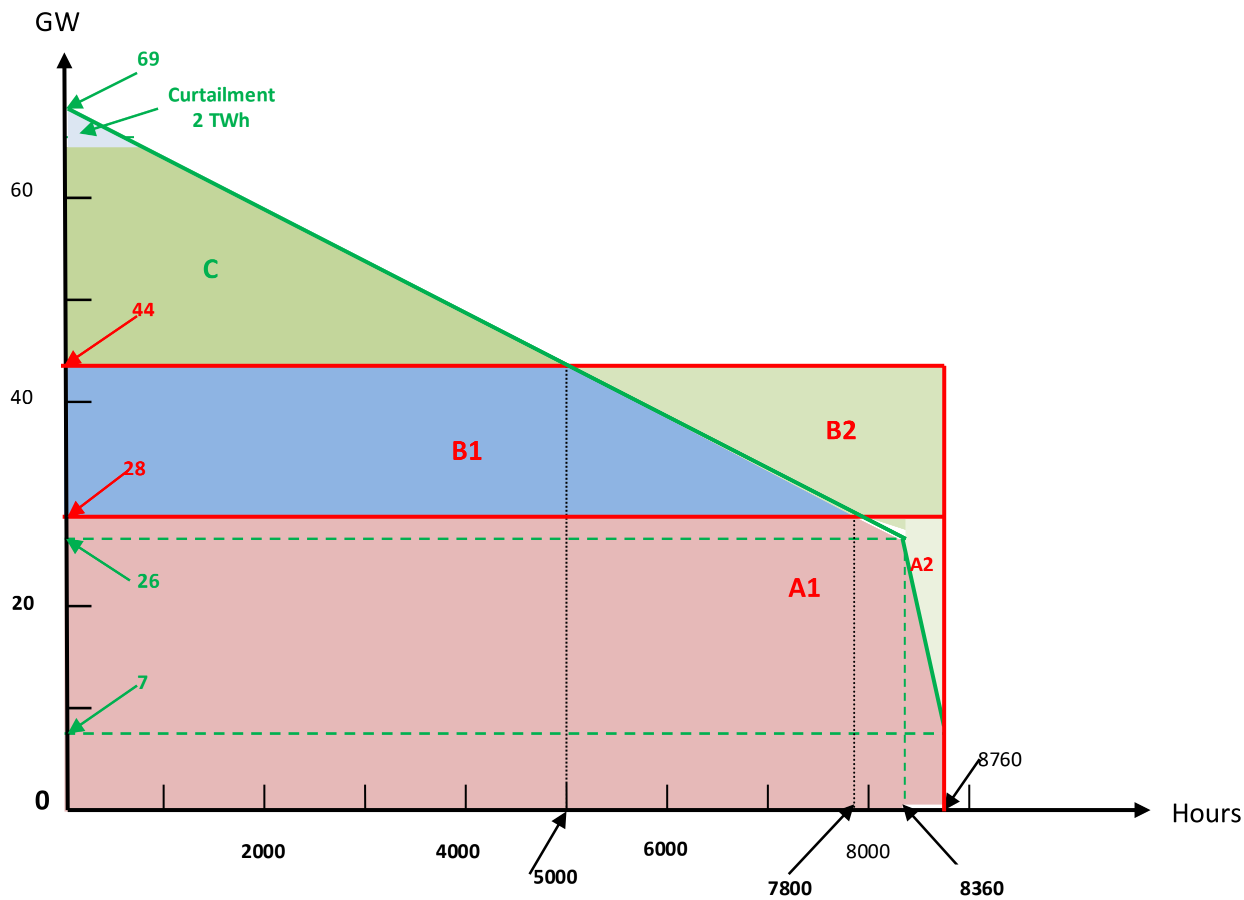


Fig. C4

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.