White Paper on the ambition of : A future low carbon Dutch Power System

Considerations on the Dutch Power System towards 2050, based on 100 % renewable energy sources, including a proposal.

1. Introduction

Based on a series of 5 KIVI meetings, organized in 2013, indicated with *EU-2050 Power Lab* (1), and two other meetings in 2014 indicated with *Solar-PV 2050 Power Lab* (2) in co-operation with Utrecht Sustainability Institute (USI) and focusing on the eventual transition to a Dutch low carbon electric power system in 2050, we felt that it is worthwhile to write down our conclusions in a white paper.

Although 2050 may seem far into the future, it is very relevant to develop a plan already now because some of the technologies and investments will need a long period to reach the desired goal. Also current shorter term plans could be brought into perspective by comparing them with a long term goal.

What would be the ultimate goal that should be reached in 2050?

The 2050 low carbon EU targets are a reduction to at least 85 % of the CO2 emission compared with the emission level in 1990. The transition of the electric system to a system with a high renewable percentage in the fuelmix, offers a major share in the realization of that EU-2050 target. In a number of policy papers already written in Europe there is the ambition to have in 2050 a CO2 neutral electricity production in Europe, based on 100% Renewable Energy Sources **(RES)**. What will this mean for a future, possible Dutch power system? To illustrate possible answers and to show a future low carbon electricity system proposal, is the main objective of this paper. The main characteristics of this proposal for a possible ***Dutch-2050 100% RES Power System***, presented in this paper, can be summarized as follows:

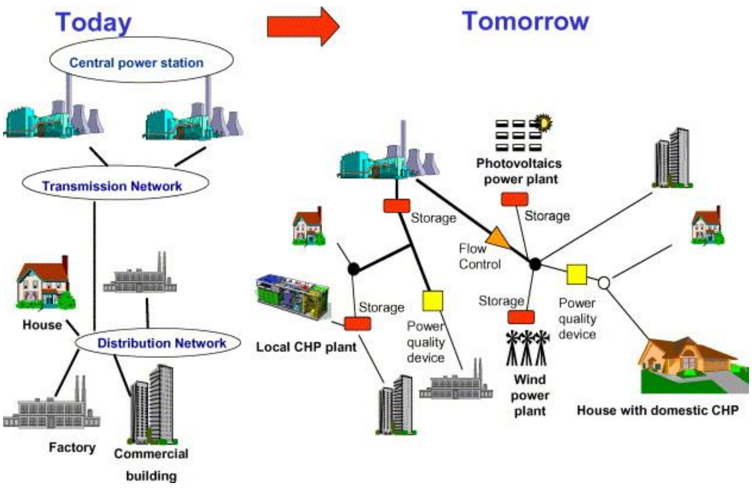
a. **Power Demand:**
   The 2050 total electricity demand is estimated to be: 130,5 TWh
b. **Electricity storage system**
   An H2-based storage system as a reserve electricity supply, able to store 13 TWh of energy being enough for about 30 days full load in case of days with low solar and wind energy. Input asks another 30 TWh generated by de RES-mix during periods when with excess electricity is generated. System efficiency will be 44%. The losses, 17 TWh could be used to cover heat demand. Curtailment will amount to a low 0,5 TWh.
   So total power demand is estimated to be **148 TWh.**
c. **Power Supply system:**
   100% RES mix to produce this 148 TWh:
   . Solar-PV: 56 GW, producing 34% of the annual demand
   . Wind offshore: 14 GW, producing 32%
   . Wind onshore: 10 GW, producing 17%
   . Other RES: 5 GW, producing 5%
   . Import green P. 5 GW, producing 12%

Based on Fraunhofer studies (4,5) we may expect that this configuration will be able to deliver a reliable and stable power system.

Financial/economical issues related to the choices in the transition to a low carbon energy system are not discussed in this paper, but we should be aware that this will be a very important force in making technological decisions!

2. The "Eu-2050 Power Lab" and the "Solar-PV 2050 Power Lab" seminar series, a short explanation.

Illustrated by the picture below, we focused on all the relevant challenges that will arise from the power system centralized as it is today, to the very complex situation of the future with centralized and decentralized power generation, short-term and long term energy storage facilities, smart grid operation and demand response.



The organization of the seminars was based on relevant topics related to the renewable energy sources en presented by excellent expert-lecturers from the universities and Dutch industries. All topics were derived from the very good study initiated by the European Climate Foundation (ECF) (6). A website is available with the obtained, detailed results. A first series consisted of 5 seminars and started begin 2013 and ended in December 2013. All the presentations and summaries of those seminars are available on the website www.kivi.nl/eu2050powerlab. They provided a good insight in the challenging task to convert our current electricity system into the desired situation for 2050. Note that we only considered the electricity system and not the complete energy system.
At the end of 2013 it became clear that Solar-PV was growing world-wide at an accelerating pace and this form of RES will play a dominant role the coming decennia in the transition to a low carbon energy mix. Especially for the Netherlands, a much larger contribution of Solar-PV power would be desirable than was planned so far. Therefore an additional two seminars on PV power were held in 2014. Based on all the knowledge gained, the current white paper could be written.

3. An approach to the Dutch 2050 electricity system based on 100 % RES fuel mix, the energy balance.

The national energy agreement for 2020-2023 aims to have a 16% RES part in the total energy consumption, resulting for the power sector in about a 50% RES share. For the subsequent decennia the ambition was mentioned to have a 100% RES power system towards 2050. The logical question that now arises is, how might such a national power system look like. We feel it as a challenge to find answers to this question! But it turns out that finding answers about this subject is not so easy. Of course 2050 is still far away and in our seminars the expert lecturers showed many new technological developments, which will definitely play an important role in the transition to a renewable energy situation. Wind energy, onshore and offshore, will further develop, resulting in lower kWh costs ((1), seminar 3, Presentation 1), an ongoing improvement of the Solar-PV technology, leading to efficiency improvement from 15% nowadays to 35% and even more in the coming decades ((2), seminar 1), new ways for converting RES-electricity to solar fuels ((2), seminar 2) to be used in energy storage facilities centralized and decentralized. All these subjects don't make it easy to predict a clear road to

the 100% RES Dutch-2050 Power System. It makes the task, how does such a system looks like, more challenging!
During both our seminars series technologies and figures have been presented for Europe and for the Dutch situation as well. Also from other studies a good impression could be derived for the Dutch situation. An important study example is from ECN with PBL (3). Some others are from Ecofys with ECN. But it should be mentioned that, studying these Dutch reports, a clear possible Dutch 2050 Power System could not be found up to now.
On the contrary other countries, especially Germany, have much clearer ideas for the desired 2050 low carbon energy targets. And based on those targets the German Umwelt Bundesamt together with the Fraunhofer Institute performed some thorough studies on the German 2050 carbon neutral power system, based on a 100% RES mix. See for instance the 2010 study from the German Unwelt Bundesamt (4). ***These studies could be used as an important guide in the development of our proposal for a 100% RES Dutch power System!***
But first some additional points will be discussed:
. Biomass as part of the 100% RES mix
. Used methodology: the Fraunhofer study as a base.
. Preconditions as energy savings, demand response.
. The expected power demand in 2050.
. The problem defining an optimal storage system, needed for the RES sources.

3.1 Avoid biomass as part of the 100% RES mix!

We think that CO2 neutrality is not sufficient. CO2 neutrality can be achieved for example by using fossil fuels and use CCS (Carbon Capture and Storage) to capture the CO2. That solution is only a short term solution since the capacity of underground storage for CO2 is limited. Moreover many people are against such a solution because the consequences are not well understood. But CO2 capture is acceptable if it is used for example in a closed loop way. An example of this is a gas turbine running on methane where the CO2 is captured and where, from the CO2, methane is synthesized again when there is a surplus of electricity. Another way to achieve CO2 neutrality is burning biomass to generate electricity. But in our opinion biomass should not be used for this purpose, since it will be needed to make other carbon based products.
So our vision is that CO2 neutrality is not sufficient and should be more restricted as outlined above. Another extra requirement we would like to impose is that the energy sources used, should be renewable to a large percentage. We don’t want to exclude for example nuclear power as a source but that source is not renewable. Since nuclear energy is restricted in many areas and not foreseen in Holland as a power source in 2050, we will not use it in our proposal.
To summarize, we would like to achieve a 100 percent CO2 free electricity production and with a high percentage of renewable sources : Solar-PV, onshore and offshore wind energy, water runoff, tidal and limited use of biomass energy. For the Dutch situation Solar-PV and wind energy will be the main suppliers for the majority of the required electrical power. And that is what we will focus on in the rest of the paper.

3.2 Methodology used and some preconditions for the proposed Dutch-2050 Power System.

A major problem in studying a proposal for a power system with high RES up to 100% is the verification, showing the system will be balanced and able to meet the power demand at every moment, the whole year round. And to perform such verification studies, one should have available a powerful simulation system, able to simulate the complex country's power system, including the power exchange with neighboring countries. It is the German Fraunhofer Institute who has developed such a complex simulation system and used it in their energy studies. Our methodology is based on the results of these German Power System simulations. Their 100% RES power system, verified to be stable and reliable, has been transferred to some degree to the Dutch-2050 power situation. A brief explanation of this Fraunhofer approach is given in the next paragraph.

3.3 "German Energy Target 2050, 100 % renewable electricity supply"

A study of the German Umwelt Bundes Amt and Fraunhofer Institute IWES, Kassel (4). This 2010 study is treating the construction of the German 2050 electricity system fully based on a 100 % RES energy mix. An important feature of this study was the verification of the complete German electricity system by a very powerful simulation system "SimEE". Germany land and sea surface was divided in a spatial array, composed of a great number of 14x14 km areas (tiles). In every tile the weather information was available on a one hour basis all year long, for the years 2006 till 2009. Also the use of the array for precise solar-PV and wind turbines was incorporated in the simulation system. Based on a great number of simulation runs, a well defined, stable and reliable German electricity system with 100 % RES resulted. The study estimates the German power demand to be 556 TWh.
The 100 % RES supply system includes a hydrogen based energy storage system, supplemented with some pumped hydro storage. The hydrogen is generated by electrolyzers and stored in available salt caverns. It is able to deliver 7% of the total annual demand; green power import is a low 3,8%. Curtailment is very low, about 0.2 % of the total electricity production.
The 100% RES mix to produce this 556 TWh is composed in the following way:

- Solar-PV: 120 GW, producing 19% of the annual demand (with η=16%)
- Wind offshore: 45 GW, producing 32%
- Wind onshore: 60 GW, producing 31%
- Other RES: 35 GW, producing 14%
- Import green P. 7 GW, producing 4%

It is remarkable that such a relatively modest share in the power supply from the storage system, together with the import of some green power as part of the total RES, is sufficient to ensure a stable and reliable electricity system. Due to the applied "demand response" and the well balanced energy storage system, also a very low curtailment results!
The next two figures 1a and 1b are part from the many figures, that are available in the Fraunhover-2010 report , and give a good insight in typical situations.

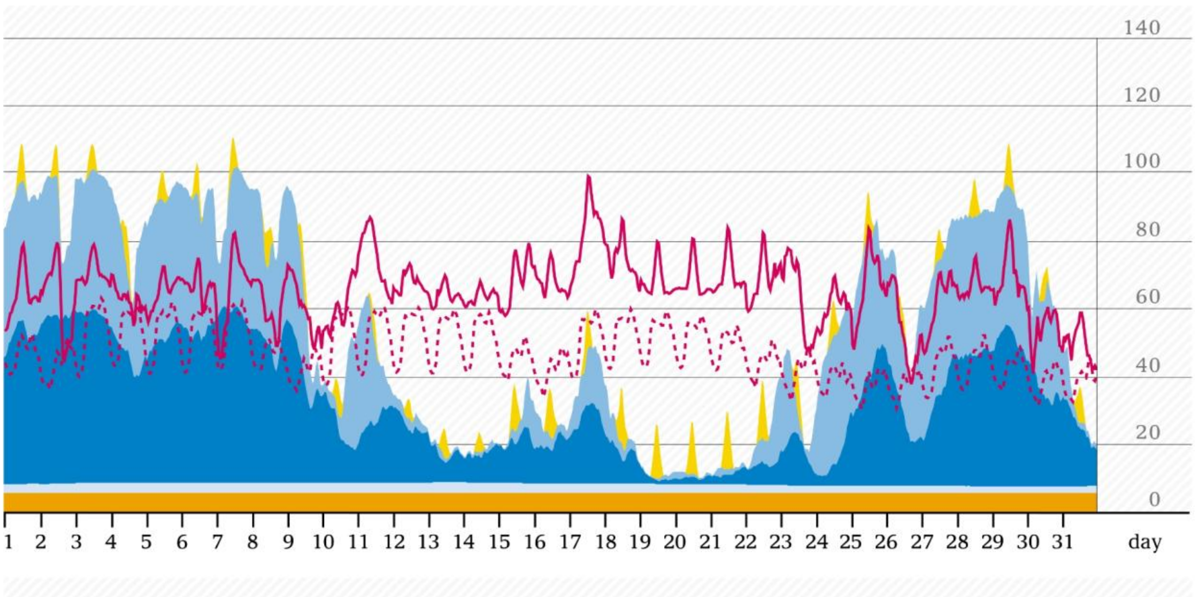


fig 1a: *simulated German 2050 RES power output and total load (solid red line) in a December month using the weather data from December 2007. Be aware of days with lot of excess power which will feed the storage system and on the other hand a series of days during which RES output is much lower than the load and the demand will be covered from the storage system. Vertical axis: power in GW.*

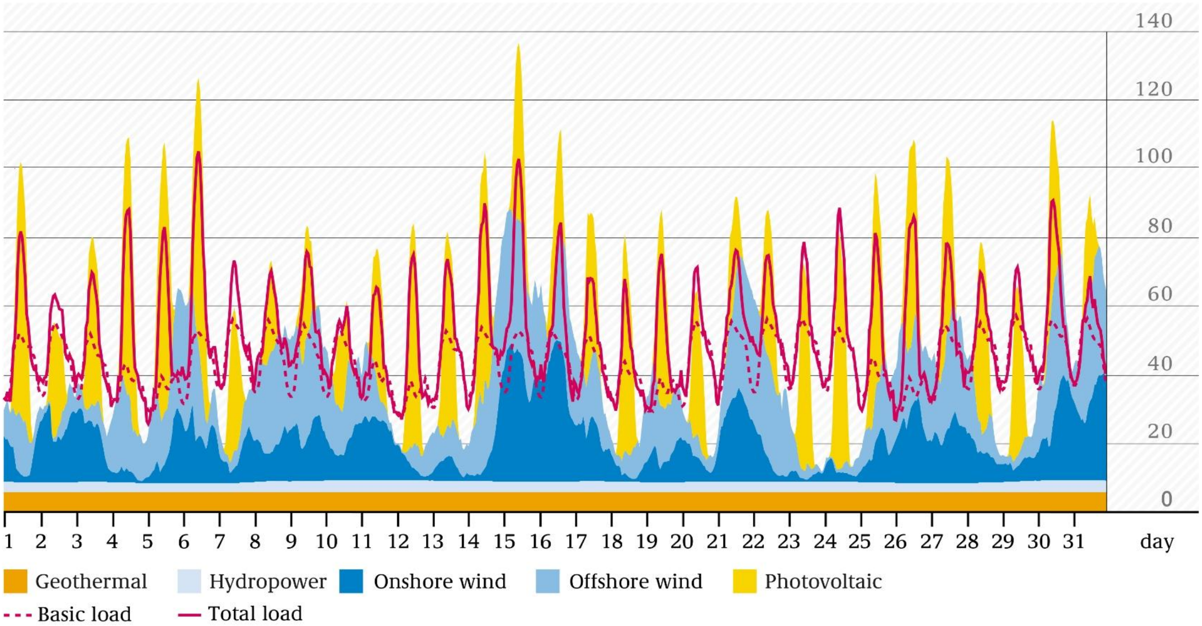


fig. 1b *The same presentation but now for an August month, using weather data from the month August 2007. Most days show excess power, building up the long-term storage capacity. Vertical axis: power in GW.*

The continuous red line shows the total load (defined as basic load (red dashed line) + heat pumps + e-vehicles + air conditioning).

The study also shows, that application of demand management and short term storage will lower the excess peaks in the solar and wind power supply from more than 100 GW to 60 GW. Accepting a low curtailment (as low as 0,5% of the total demand) the required power capacity of the electrolyzers can be limited to 44 GW.

The next figure 2 from the Fraunhofer 2010 report shows the difference between demand and supply (residual load) with the indication for the required power of the electrolyzers.

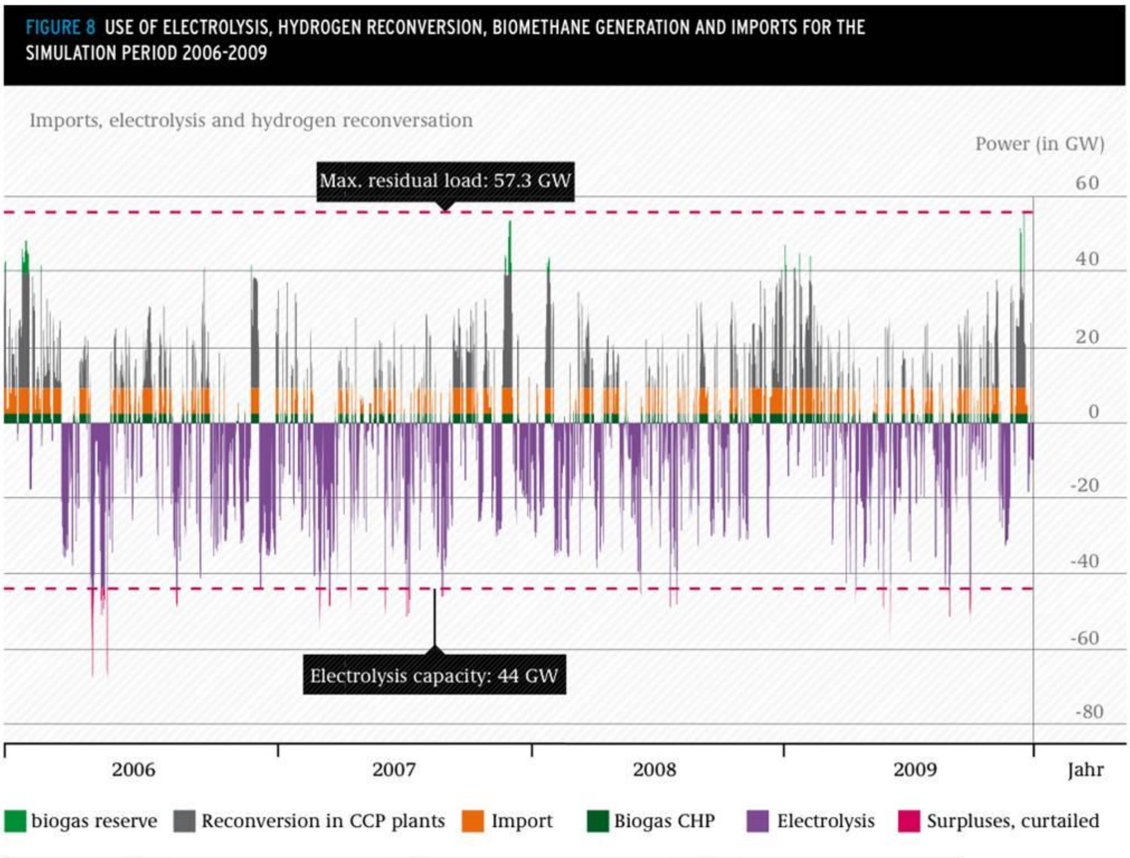


Fig. 2: the 2050 simulation, showing the difference between total demand and generated electricity using the meteorological data from the years 2006-2009. Less than one percent of curtailment is happening with a proposed electrolysis capacity of 44 GW.
It can be seen that curtailment occurs *quite* seldom.

3.4 Some preconditions necessary for a balanced and reliable power system

Before presenting the envisioned Dutch Power System we want to mention that we have taken into account the main factors that are needed to arrive at a balanced and reliable system.
Briefly noted those are:
. energy saving where possible,
. power demand response to an acceptable degree to limit peak power demand and to improve the balance between the variable RES power supply and demand
. short-term energy storage, mainly decentralized, for improving the day-night power demand and further improving the energy supply-demand balance.
. smart grid implementation supporting the power demand and local short-term storage facilities,
. a long-term, season-bridging storage system, serving as the reserve electricity system and generated from the installed RES sources. As in the Fraunhofer study (3) this based on a large-scale hydrogen storage system,
. a sufficiently strong electricity network, able to transport the large amount of decentralized PV-electricity and with strong connections to neighboring countries, enabling a good power exchange.
All these preconditions are thoroughly discussed in our seminars (1) and studied in detail and well described in a number of papers and will not be further explained in this paper.

3.5 The Dutch-2050 power system, an approach

A first issue to address is how much electrical energy is needed on a year basis and what is the required maximum power in the year 2050. The drive for energy saving will lower the electricity use with about 15 % from the 120 TWh produced in 2010. But due to the switch to electric vehicles to some degree, the use of heat pumps for space heating and a growing need for aircon systems the electricity demand may rise to 131 TWh.
Furthermore some curtailment is unavoidable and also extra electricity input is required to build up long-term storage, large enough to be sure the system is stable and reliable to deliver the electricity demand every hour the year round. The target for the proposed Dutch system is to have a curtailment percentage lower than one percent of the produced energy.

3.5.1. The long-term storage system as the reserve power supply

This storage system has been derived in a straightforward way from the Fraunhofer Storage System (4). The system is based on the conversion with electrolyzers of the surplus RES electricity into a solarfuel (H2 preferably, although conversion to methane may be considered as well). When required the stored solarfuel is reconverted into electricity and delivered to the grid. This reconversion can be performed by gas-turbines suitable to handle Hydrogen as the fuel input and fuel cells (2, seminar 2). See fig. 3a and 3b for a simplified block diagram. Total system efficiency is 44%, as a result of the electrolyzer efficiency (80%), the H2 storage efficiency (93%) and the efficiency of the re-electrification (59%). Main figures for the hydrogen based system are given as follows:
The solar fuel storage system has a 13 TWh capacity, this is 10 % of the total basic demand (131TWh), sufficient for about 1 month demand.

Table 1: *Long-term Storage System figures*

Total system efficiency:	44 %	System loss: 17 TWh
Electrolyzer		
Input:	30 TWh	Efficiency: 80 %
Input power (central. + decentral.):	15 GW,	annual use: 2000 hours/a.
Generated solar fuel:	658 ton H2	Storage efficiency: 93 %
Re-electrification		
Output	13 TWh	Efficiency: 59 %
Total output power capacity	10 GW	annual use: 1300 hours/a

3.5.2 The total ductch electricity demand in 2050 will therefore be:

Table 2

Basic demand after 15 % energy saving:	**106 TWh**
Additional demand:	
Aircon:	2.5 TWh
Electrical vehicles	12
Heat pumps for space heating:	10
	+-----------
Total demand:	130.5 TWh
Extra demand due to:	

Inevitable curtailment of local generation:	0.5	TWh
Losses of the H2-storage system	17	TWh
	+------------	
Total electricity demand 2050	**148**	**TWh**

The peak demand power is estimated to be 25 GW

3.6 How to cover this demand with a 100 % RES Supply system.

A second issue to address is what part should the three main sources (PV, wind on land and wind on sea) take to satisfy the total energy demand. The Fraunhofer approach and the 100 % RES mix for the German 2050 system was based on advanced technologies available in the years before 2010. Well acceptable, but during the recent past years Solar-PV is growing strongly. However it did not have a dominant part in de Fraunhofer RES mix. Based on our last two seminars, dealing with Solar-PV (2), we may expect that solar electricity will dominate much more in the coming decennia with efficiency figures higher than nowadays, also in the Netherlands. Using this expectation we made a balanced plan for the Dutch energy system 2050. Hereby is taken into account that the Dutch part of the North Sea has an area that is 1.5 times as large as the area of the mainland. Therefore much more use of wind power at sea should be used. Another feature is the application of 20 % demand response, as in the Fraunhofer study. The ratio for the proposed mix, solar-PV/(solar-PV + wind energy) being 0.4 , has been chosen trying to achieve an economical optimum. One could choose for much more PV for example but this would require more seasonal storage and creates larger peak powers.

How will the demand be covered?

Table 3**:** *Dutch-2050 Power System with 100% RES*

	Installed Power	Yield/a	Remarks
1. Solar-PV	**56 GW**	**50 TWh**	0.3 GW end 2012
. efficiency	35%		4 GW expected in 2020
. hrs/yr:	900 h		
. required net PV:	159 km²		10x16 km², available roof area is 400 km²
2. **Wind-offshore**	**14 GW**	**48 TWh**	4.45 GW planned in 2023
. hrs/yr	4000 h		
. req. sea area km²:	1360km2		Gemini proj. 600 MW, 68 km²
3. Wind-onshore	**10 GW**	**25 TWh**	Nat. En/gy Agr/mnt: 6 GW
. hrs/yr	2500 h		
4. Other RES	**5 GW**	**8 TWh**	wave + tides energy plants, Geothermic power
. hrs/yr:	1600 h		
5. Import green p.:	**5 GW**	**17 TWh**	Hydro storage, Norway.
. hrs/yr:	3400 h		
		+ ---------	
Total RES:		***148 TWh***	

Is the total reserve power able to cover the peak power demand?

The expected peak power demand is estimated to be 25 GW, but might be reduced to 20 GW due to the applied demand response in combination with short term storage and large-scale smart grid.
This will be covered by:

. Reconversion power:	10 GW
. Other RES	5
. Import green power:	5
	+----------
Total reserve power:	**20 GW** **in balance with the peak power demand**

As in the German proposal the expected curtailment will be low (0,5 TWh, see 1.1), due to the implemented demand response and applied (mainly decentralized) short term (day-night cycle) storage, enabling the power demand to follow quite well the variable RES-electricity supply curve.

Although the proposal is based more or less on the approach of the Fraunhofer proposal and for that reason should be stable and having a good supply reliability, we must stress, that this proposal has not been verified by any simulations , using real Dutch data.
We must emphasize, that such a verification system is essential and should be made available.

Fig. 3a and 3b shows the coherence of the different energy and power flows in a simplified block diagram.

Fig3a: *the energy flows*

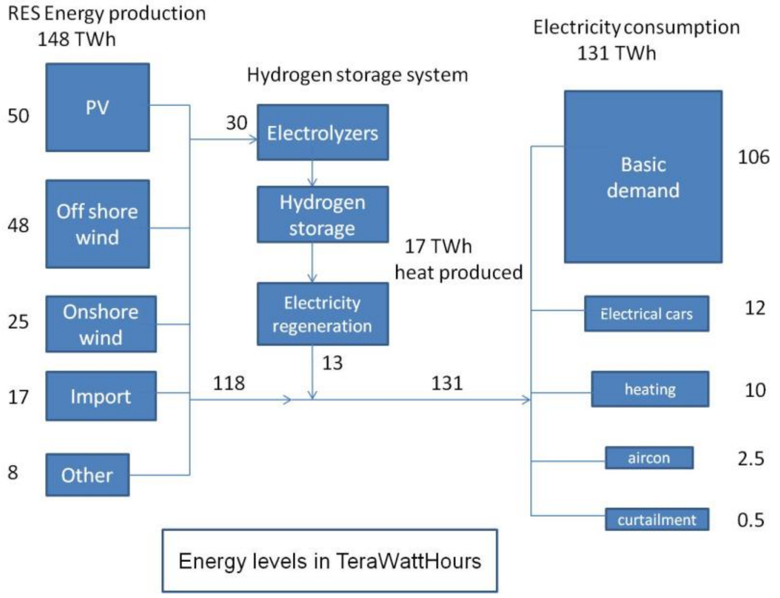
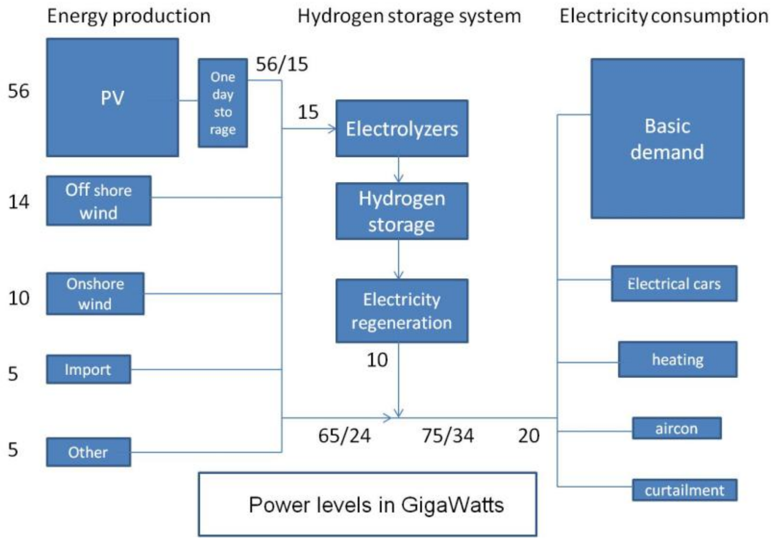


Fig. 3b: the power flows



By providing a one-day storage facility for the PV power, the maximum PV power can be reduced from 56 to 15 GigaWatts which fits better in the total power flows.

4. Important questions still difficult to be answered

Is the proposal for the Dutch-2050 100 % RES Power System sufficiently feasible? Looking to the required land- and sea surfaces for the solar-PV and windparks, this should not be a technical problem. The seminars have shown that the potentials that are available in the Netherlands are clearly sufficient. But social, negative reactions may be expected especially around a large part of RES energy from onshore and near-shore wind-parks, forcing to other choices of the RES mix. In our proposal we have limited the amount of onshore wind to a modest amount and have chosen to use the available roof top area to generate a large amount of electricity instead. Another issue is if the long term electricity storage proposal, as defined in table 1, will be able to guarantee a reliable power supply. Are the supposed total installed power facilities sufficient to support this requirement? Is the electricity grid sufficiently constructed to carry the enormous power? This kind of questions will be discussed in this chapter.

4.1 A 100% RES based system forces to create a reliable reserve power system

In the proposal the H2-based reserve power system has the capacity to cover the demand for 30 days when serious lacking of solar and wind power appears. This is reasonably in accordance with the results of the Fraunhofer 2010 study. But an important factor, strongly influencing the needs for an extensive long-term storage system is the development of the European electricity grid. When fully developed, enabling the energy transport throughout Europe with low losses, this will seriously reduce the demand for a relatively large storage capacity up to less than 5 days, as was shown in de recent Fraunhofer 2014 study (4). For the Dutch-2050 situation this will mean, that surplus electricity largely will be exported and when needed green power is available from abroad. Therefore the requirements for long-term storage capacity could then be reduced to less than 5 days! But the implementation of such an EU-wide, strong electricity grid during the coming decennia, has not only financial barriers, but political barriers as well!

4.2 Excess RES power: are the strong peaks on sunny and windy days manageable?
Looking to this Dutch-2050 proposal you may expect high power peaks in the Solar-PV and wind-parks on sunny, windy day. Top-peak could be as high as 80 GW, much more than the peak demand of 25 GW. The resulting excess power should be used for the storage system via the electrolyzers, requiring a very high input power capacity of the electrolyzers in total. But looking to the Fraunhofer studies, which are based on very thorough simulation runs, such situation appears to be very rare. It is not clear however how to best manage the high peak power levels that will occur in the network. This is worth a detailed separate study where different scenarios are compared with each other including parameters like : where to install the electrolyzers in the network, the use of local storage and the strengthening of the network. But based on the detailed Fraunhofer analysis we estimate that in our proposal the input power capacity of the electrolyzers can be moderate too: 15 GW. Still a low curtailment of the excess power results.

4.3 Is hydrogen a good choice as intermediate storage medium?
In our proposal we opt for hydrogen as the intermediate medium for storing energy to convert the generated excess power. We may consider two other carriers as well : methane and ammonia. Hydrogen has our preference at the moment because the efficiency of the total process is the highest in case hydrogen is used, about 44 % as overall efficiency. Each carrier has its advantages and disadvantages but all three could work.

The problem of hydrogen as carrier is that storage is not so easy. The use of hydrogen as a storage medium in local, decentralized energy storage systems and in residential surroundings, may be a problem nowadays. But for large-scale, centralized application there are useful options. One solution is highly pressurized hydrogen stored in salt caverns. Many experiments have already been performed in storing hydrogen in this way. An important project, dealing with this subject is the EU project HyUnder (www.hyunder.eu) studying the large scale H2 storage, and will ending mid 2014. ECN is strongly involved in this project (2). It is recommended to install electrolyzers and fuel cells or hydrogen turbines close to where the storage is done to limit hydrogen transport.

Methane is also a possibility. The generated hydrogen from the electrolyzers has to be converted in a second step to methane by using CO2, lowering storage system efficiency to about 38%. *But the major problem is where to get the CO2 from*. In the medium term this could be obtained from point sources in industries that emit CO2 (like cement industry). But in the long term the CO2 should be used in a closed loop manner we think. So, when the gas turbine burns methane, or fuel cells using methane, the emitted CO2 should be captured and stored for later use to generate methane again. But large-scale CO2 capturing can be seen as the big problem in the methane variant. On the other hand the big advantage is that there is a huge gas network already available with sufficient storage capacity.
Two issues should be considered furthermore: make the conversion of electricity to methane as efficient as possible and secondly study the CO2 storage requirements preferably in above ground tanks. In the last 2 presentations two new promising and challenging methods were presented enabling the conversion to methane at normal temperature and pressure. The first one was based on plasma technology and the second one on nano catalyzation, both methods

especially attractive for decentralized application (2, seminar 2). Still in those methods CO_2 has be available.

Another third possibility is ammonia (2). The big advantage of this is that it is carbon free and nitrogen is ample available. It can also be stored in liquid form under less than 10 bars. In the chemical industry there is a lot of experience with ammonia production and storage so it is a well proven technology. Those available technologies should be studied and examined where to be improved so that ammonia can be used as energy carrier. But a difficulty with ammonia is its dangerous toxicity.

Regarding the electrolyzers as a common very important element in the discussed methods, it should be mentioned that the cost of generating hydrogen is still too high nowadays. So the cost has to come down. Another important aspect is that no rare and expensive materials in the electrolyzers should be used because an enormous capacity of electrolyzers will be needed, not only in Holland but in Europe and worldwide too.

5. Our conclusions

Our conclusion is that, based on data provided by the excellent presentations in our series of seminars and the thorough German reports, a Dutch-2050 100% RES Power System with nearby 100% CO_2 free way of generating electricity is possible. We may summarize some consequences of this proposal
This proposal will have many consequences. We would like to focus on those that require long term development and also those that may come up in the future.
A first already mentioned issue is the availability of reliable low cost electrolyzers. The life time of electrolyzers is also an issue because they will have to operate under large varying input of power.
A second issue is the exploration of enough salt storage capacity in the salt layer in Holland, suited to store large quantities of H_2. Based on one of the presentations in (2), the Dutch possibilities are promising and need not to be a restrictive factor. Furthermore experiments are already now done in Germany in similar types of salt layer.
A third issue is the consequences for the electricity network. For example on the local electricity grid, problems may occur when all the houses, having efficient PV panels on the roofs, are feeding into the local transformer. Each roof could generate about 10 kW of power. Another aspect is that the power delivered to the grid, that needs to be stored, will later be returned to the grid with a maximal efficiency of 40 percent. Taking also into account the write off and maintenance of the storage system, the price of electricity taken from the grid will be much higher than the price people will get from delivering to the grid. This will stimulate to find solutions for local storage in the homes.
But the most important action to be taken is to perform a detailed simulation on this proposal and other new proposals to verify their soundness but also to look for the best possible economical optimum for the needed investments.

References

(1) EU 2050 Power Lab, 5 KIVI+USI seminars in 2013
(2) Solar-PV 2050 Power Lab, 2 KIVI+USI seminars March and April 2014
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(3) ECN + PBL, 2011 “Naar een schone economie in 2050: routes verkend, hoe Nederland klimaatneutraal kan worden.”

(4) German Umwelt Bundesambt and Fraunhofer Institute IWES, Kassel, 2010: “German, Energy Target 2050, 100% renewable electricity supply”
(5) Fraunhofer Institute IWES, Kassel, 2014: “Storage needs for 100% renewable electricity in Germany and Europe-scenario analyses”
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