The Dutch Hydrogen Economy in 2050

An exploratory study on the socio-economic impact of introducing hydrogen into the energy system of the Netherlands

Catrinus J. Jepma *New Energy Coalition*

Eise Spijker *JIN Climate and Sustainability*
Erwin Hofman

March 2019

Acknowledgement

This study on the 2050 socio-economic impact of introducing a hydrogen economy in the Netherlands has been commissioned by N.V. Nederlandse Gasunie and carried out by New Energy Coalition and JIN Climate and Sustainability during November 2018 – March 2019.

The research team thanks the advisory committee, consisting of Prof. Ad van Wijk (TU Delft; New Energy Coalition), Hans Duym (Gasunie), and Harold Veldkamp (New Energy Coalition), for their extensive comments and suggestions.

Groningen, 13 March 2019

Table of contents

Introduction **4**

2050 hydrogen development scenarios **5**

The scenarios considered *6*

The ETM model *7*

Results **7**

Employment impacts *8*

Overall energy system costs *9*

Mitigation impacts *9*

Energy imports and exports *10*

Discussion **11**

Towards the hydrogen economy *11*

Some generic socio-economic considerations on the model results *14*

The scenarios in the perspective of other studies *16*

Conclusions **19**

References **21**

Annex I: ETM scenario model inputs **23**

Demand **25**

Households and Buildings *25*

Transport *26*

Industry *26*

Agriculture *27*

Supply **27**

Electricity *27*

Hydrogen *28*

Storage *28*

Flexibility *29*

Conversion *29*

Annex II: Modelling constraints, limitations and key assumptions **31**

Introduction

Within the energy transition process in the EU and its Member States, the attention for the role of carbon-neutral hydrogen as a serious part of the future energy mix seems to be growing strongly, especially during the last few years. This is equally the case in the Netherlands, where typical issues in the discussion are:

1. how strong will the role of hydrogen be in the future Netherlands' energy system;
2. under what conditions can 'green' and 'blue' hydrogen compete with 'grey' hydrogen and comparable energy carriers/feedstocks;
3. to what extent can infrastructure, technology and knowledge traditionally used for natural gas be used for hydrogen; and
4. what policies and measures will be needed to 'green' the energy molecules and to introduce hydrogen in the various economic sectors as a powerful strategy, in particular?

Within the expanding body of research and literature, little attention so far has been given to the potential impact of moving towards a more hydrogen-based economy on the broader society and economy (e.g. in terms of growth, jobs, competitiveness, innovation, energy imports, greenhouse gas emissions, and overall energy system costs). In this report we try to shed some light on this issue by exploring the following research question:

> *What can be said about the long-term (2050) possible socio-economic impact of a switch of the economy of the Netherlands that is primarily fossil energy-based towards an economy based on renewable energy, including a serious role for hydrogen?*

Within the EU, the 'hydrogen economy' is already gradually developing. To date, a serious number of piloting initiatives towards generating or implementing carbon neutral hydrogen (or derived syngases) has been set up, especially also in North-western Europe (Hydrogen Europe, 2019) and the Netherlands in particular (Hoogma, 2017). These pilot initiatives typically try to answer questions related to the abovementioned techno-economic and policy issues (including technological assessments, business case analysis, policy support measures, etc.), but rarely explore the broader socio-economic implications of an expanding 'hydrogen economy'.

There are some enabling conditions why the Netherlands and its surrounding countries have a good prospect to develop into one of the EU pioneering areas in the transition towards a 'hydrogen economy'.[1] A typical characteristic of carbon neutral hydrogen is that it has similar properties as natural gas: e.g. it is relatively easy to transport via pipelines and store underground (particularly in salt caverns). While some modifications to the existing gas infrastructure are required to be able to serve the hydrogen economy, the required knowledge, expertise, and experiences for this seem to be well covered by the expert system in the Netherlands.

Also, for the production of either blue or green hydrogen in substantial volumes, large volumes of green power (i.e. green hydrogen) and/or large flows of natural gas are needed, as well as CCS- or CCU-related transport and storage facilities (i.e. blue hydrogen). For this the Netherlands may be comparatively well positioned to develop into a future Northwest-European hydrogen hub, as:

- large amounts of offshore green power from Norway, Denmark, Germany and the national North Sea gas production are coming onshore at the Dutch coast, primarily in the Northern part of the country;

---

[1] See also the recent report by the working group H2 (Werkgroep Waterstof, 2019).

- the Netherlands has one of the most concentrated (and easy-to-retrofit) gas infrastructure systems of Europe with interconnections towards all neighbouring countries and beyond; and hosts one of the most active gas trading hubs of Europe (TTF);
- the Netherlands currently (2019) already consumes some 8 bcm of hydrogen annually, mainly taken up as a feedstock by the relatively large (petro)chemical and steel industry, and in fact belongs to the larger industrial hydrogen producers within the EU (although this hydrogen is still predominantly generated via steam reforming natural gas);
- the degree of concentration of transport systems, as well as of the built environment is relatively high, which makes it logistically comparatively easy to introduce serious volumes of hydrogen into the energy system;
- the Netherlands has substantial salt cavern capacities both onshore and offshore that may typically be developed for seasonal hydrogen storage; moreover there is ample access to empty gas fields, especially offshore, that may be used for CCS as a component of blue hydrogen production;
- The gas- and energy system integration-based knowledge base in the Netherlands is traditionally high.

In view of the potential comparative advantages of the Netherlands to develop into a hydrogen-hub, the obvious question is to what extent the economy of the Netherlands can benefit from growing towards a hydrogen based energy system.

2050 hydrogen development scenarios

Despite the described comparative advantages of the Netherlands, a hydrogen economy does not develop automatically. Sufficient supply-push and demand-pull measures have to be taken in order for different sectors to increase the uptake of hydrogen, and for economic actors to invest in scaling up the production of blue and green hydrogen, and other parties to enable the safe and reliable transport and storage of hydrogen.

In this report we do not discuss what specific policies and measures are needed to foster the development of a hydrogen economy. Instead we use the Energy Transition Model (ETM, 2018)[2] to simulate and estimate the socio-economic impacts of three possible futures (or scenarios). We use the parameter values of the existing 'RLi -95% specification' – that can be found in the online version of the model – as a starting point for our hydrogen uptake scenarios. This RLi – 95% specification was developed by Quintel Intelligence (2018) on behalf of the Dutch Council for the Environment and Infrastructure (*Raad voor Leefomgeving en Infrastructuur*), and is described in more detail by Kerkhoven, et al. (2015). It includes a tailored set of parameters used to model a possible low-carbon future with 95% lower energy-related greenhouse gas emissions. Based on these starting point parameters (which do not consider any uptake of hydrogen at all), specific parameter values have been adjusted to allow us to simulate the uptake of hydrogen in different sectors for energy applications. Note therefore that the RLi 95% specification is not used as a scenario in our study, but just as a basis to set the parameters that will allow to get to a sufficiently green energy system by 2050.

Note also that the ETM model only focuses on the energetic applications of hydrogen and other fuels. For that reason the future uptake of hydrogen as a feedstock needs to be added as a separate

---

[2] The model is subject to frequent updates. For this study the January 2019 specification of the model was used.

component in providing an overview of total national hydrogen uptake. With respect to the share of hydrogen being taken up as feedstock, recent studies assume for the Netherlands shares by 2050 ranging between about 30 and 45% (Hers, et al., 2018, p. 17; Gigler & Weeda, 2018), while acknowledging that the feedstock share of hydrogen currently is a large part of the national total.

The scenarios considered

We consider three different scenarios over the timeline 2015-2050. The scenarios differ from each other on four key characteristics of the energy system and energy and climate policy regime, namely:

(1) the degree to which our country aims to become self-reliant on energy and strives to produce the renewable energy it needs as much as possible domestically;
(2) the degree to which the Netherlands wants to achieve the 95% emissions reduction target rather than the 80% target;
(3) the degree to which limiting the overall energy system costs is given priority as a policy target, rather than other societal targets;
(4) the degree to which the Netherlands tries to be a European frontrunner towards a hydrogen economy by strongly supporting hydrogen uptake not only by the industry but also in mobility and the built environment.

Scenario 1 considers a modest uptake of hydrogen for energetic applications by 2050, of about **233 PJ** per year of the total annual energy use of about 2,322 PJ. Hydrogen is used mostly in industry in the Netherlands. The domestic production of hydrogen does not come off the ground significantly. There is 5 GW of offshore wind capacity dedicated to hydrogen production, along with some electrolyser capacity for converting electricity surpluses. Some 70% of the hydrogen used for energetic applications in the Netherlands is therefore imported (next to all the hydrogen needed as a feedstock).

Scenario 2 is strongly focused at creating a green energy system such that close to the 95% (energetic) CO_2-emissions reductions can be achieved by 2050. Also, as much as possible it is tried to minimise import dependency of energy and hydrogen in particular. The overall impact on employment is considered more important than the overall cost of the energy system. However, to develop into a typical innovative hydrogen frontrunner is not considered the most important; rather to really green the economy is seen as the key objective. The hydrogen demand in this scenario is **355 PJ**, with a total annual energy use of about 2,398 PJ.

Scenario 3 typically tries to maintain the Netherlands as an energy hub that is open for international trade and develops strongly as an innovative frontrunner towards a hydrogen economy. Uptake of hydrogen in this scenario therefore increases compared to the other scenarios. Because it is not considered to be necessary to produce hydrogen domestically as much as possible, there remains a clear reliance on hydrogen imports from low-cost regions. The hydrogen penetration in all sectors benefits from the strong innovative spirit to creating a hydrogen economy. The hydrogen demand in this scenario is **463 PJ**, with a total annual energy use of about 2,395 PJ.

For a more detailed overview of selected parameter values in our study, see Annex I.

Table 1. Overview of the key scenario characteristics

	Self-sufficiency for energy	Achievement of 95% emissions reductions	Priority for overall energy system costs	Netherlands as a hydrogen frontrunner
Scenario 1: Subdued hydrogen uptake and production	o	o	o	o
Scenario 2: Self-reliance on energy, strong focus on greening including domestic hydrogen production	+	+	o	o
Scenario 3: Strong hydrogen hub, hub function with significant hydrogen imports	o	o	+	+

The ETM model

The ETM model allows us to change a broad range of parameters, including:

- energy system demand data in different end-use sectors, including households, buildings, transport, various industries and agriculture;
- energy system production/supply data and supply data in terms of heating, electricity, transport fuels, including hydrogen;
- energy system and energy technology costs and prices.

The model also allows us to alter the functions of the electricity system in terms of the merit order of electricity system balancing options, flexibility, and imports/exports.

In our simulation we refrained from altering cost data as well as parameters regarding technological features, such as thermal efficiencies, efficiency improvements, load factors, etc. relative to the starting point. We mainly focussed on key parameters that affect the domestic demand and supply of hydrogen as well as the electricity system dynamics (e.g. for what purpose excess renewable electricity is used).

On the demand side, key simulation parameters included the penetration rate of hydrogen boilers used for heating application in households, buildings, industries and agriculture, either via stand-alone boilers, or by way of hydrogen fuelled district heating systems. For fuel demand in transport we simulated a higher penetration rate of hydrogen fuelled vehicles.[3] For an impression of the model limitations, see Annex II.

Results

As far as the results are concerned, we will distinguish between: the employment impact; the overall energy system costs; the climate change mitigation impact; and the effects on energy imports and exports.

---

[3] We exclude international shipping and aviation from the simulation analysis.

Employment impacts

As far as the employment related to the energy activities is concerned, the ETM model indicates for 2015 a total number of jobs (full-time equivalents, FTE) in the Netherlands of about 58,700.[4] The major share of this is related to maintenance (46%), followed by installation (25%) and production (17%). The results (Table 2) show that greening the energy system towards an almost carbon-neutral system generates a considerable number of additional jobs. In scenario 1, relative to 2015 some 140,000 extra full time jobs will be created, and in the scenarios 2 and 3 even significantly more, partly because the extensive introduction of (decentralised) renewable energy systems and innovative introduction of hydrogen applications is assumed to have a somewhat stronger indirect employment (i.e. multiplier) impact. Scenario 3 employment is lower relative to scenario 2, considering the higher level of hydrogen imports which would create jobs in other countries.

Table 2. Employment in the energy sector in FTE

	2015	**2050**		
		Scenario 1	**Scenario 2**	**Scenario 3**
Decommissioning	6,400	17,000	23,600	23,000
Maintenance	27,000	62,900	103,700	98,700
Installation	14,900	85,900	138,800	125,400
Production	9,800	33,500	53,900	49,800
Planning	600	1,600	3,600	2,300
Total	**58,700**	**200,900**	**323,600**	**299,200**

These employment figures refer to the entire energy system, including hydrogen. A recent study by CE Delft (Leguijt, et al., 2018) that estimates the lasting employment impact (in FTE per year) of the introduction of hydrogen only, concluded that by 2050 the additional employment would be in the range of 17,500 to 75,000, and in addition one-off employment was created ranging from 850 to 4,750 FTEs. If one takes the average as a crude ballpark figure, the hydrogen economy impact would create in the order of 50,000 jobs by 2050. By comparison, the figure in our assessment could be somewhat higher considering for instance the employment difference between our scenario 1 (limited hydrogen production and use) and scenario 3 (embarking on a hydrogen economy).

On the whole, it is complex to translate a strong innovative development towards a specific technology into a job multiplier, i.e. a factor describing to what extent a job directly related to the extending energy activity will contribute to creating new jobs in related innovative and surrounding activities. In the literature, job multiplier estimates from advanced technology employment are mentioned ranging from about 2 to 5, or even more (CCAT, 2008; Goos, et al., 2018). In this study, we have taken the conservative assumption of a job multiplier related to the intensive greening of

---

[4] Please note that the employment module of the ETM model has a limited coverage of the different sectors. The current version covers employment for households, buildings and the energy sector but does not yet include employment data for agriculture, industry and transport. As such we consider our estimates to be relatively conservative. In a recent report of SER (2018, p. 17), the total employment in the energy sector (2016) was estimated 125,000 FTE, of which 52,000 in sustainable energy activities. Unlike the ETM model, SER also included energy-related jobs from activities in other sectors.

the energy system and moving towards the hydrogen economy (scenarios 2 and 3) of 1.5 only. In other words, we have taken a conservative assumption towards the employment multiplier.

Overall energy system costs

The overall energy system costs consist of the following components: network costs, fuel costs, non-energetic fuel costs, electricity costs, heat costs, and hydrogen costs. By 2015, the total energy system costs were € 31.39 billion, or some 4.6% of the gross domestic product of the Netherlands. From Table 3, it is clear that greening the energy system will substantially raise the overall costs of the energy system, to about double the current (2015) level by 2050 in scenario 1 and even more in the other scenarios. Because the number of households during the period considered is assumed to grow only to a limited degree, the energy costs per household are expected to increase significantly, although it remains to be seen how the costs will be distributed between households and production sectors. The higher energy system costs in scenario 2 can be explained by the high level of self-reliance in domestic hydrogen production and transmission, translating into higher costs for renewable electricity generation and network costs.

Table 3. Overall energy system costs in billions of euros

	2015		**2050**	
		Scenario 1	**Scenario 2**	**Scenario 3**
Network	4.15	9.03	16.09	9.76
Fuel	6.95	1.40	1.39	1.39
Non-energetic fuel	3.67	13.94	13.43	13.26
Electricity	7.64	18.52	24.83	17.68
Heat	8.98	19.73	17.70	17.20
Hydrogen	0	4.99	13.94	11.70
Flexibility	0	0.30	3.50	1.31
Total	**31.39**	**67.89**	**90.89**	**72.31**

Mitigation impacts

The overall energetic CO_2 emissions of the Netherlands amounted to some 169 MT in 2015 (155 MT in 1990). The 95% emissions reduction target has been based on the 1990 figure, so the maximum emission level in 2050 should be 7.75 MT if the 95% target is chosen. In scenario 1, the latter target is not reached: the 2050 emissions level was projected to be about 33 MT. This corresponds to an emissions reduction of 79% compared to 1990, which, however, is at the edge of, albeit slightly below, the range (80-95% reduction) as defined by the European Council.

The scenarios 2 and 3 are within the 80-95% target range, and mark energy futures for the Netherlands that satisfy these mitigation targets, although scenario 2 gets close to the 95% of the target range whereas scenario 3 stays close to the 80% level. A common characteristic of all scenarios is that industry and transport will be responsible for the bulk of the remaining (energetic) CO_2 emissions, because in households and the category of 'other buildings', as well as in energy conversion, CO_2 emissions will be cut down almost completely by 2050.

Table 4. Energetic CO_2 emissions in Mt

	2015	**2050** **Scenario 1**	**Scenario 2**	**Scenario 3**
Industry	64.9	19.2	6.9	17.3
Transport	34.4	8.0	1.5	6.0
Households	27.9	1.1	0.7	1.9
Other buildings	21.6	1.8	0.7	1.7
Agriculture	8.5	2.8	0.6	3.1
Energy	11.5	0.6	0.2	0.5
Others	0.3	0.2	0.2	0.2
Total	**169.1**	**33.7**	**10.8**	**30.7**

Energy imports and exports

The net imports and exports of energy by the Netherlands in 2050 are projected to typically change due to the fact that natural gas is imported rather than exported because of the almost complete phase-out of the domestic gas production. Also coal will no longer be imported due to the expected closure of all coal-fired power plants. With respect to oil, the assumption has been made that our country typically acts as a transition hub for oil, where the imported crude oil is converted into oil derivatives, to be then exported back to the world market, mostly in the rest of Europe. This explains why the balance of the imports of crude oil and the net exports of oil products is assumed not to change, because this balance does not typically affect the hydrogen economy. It explains also why we included in the table the energy balance excluding oil.

As far as hydrogen is concerned, there is a clear difference between scenarios 1 and 3 on the one hand, in which there is a significant net import of hydrogen from the international market, and scenario 2 on the other hand, where our country is self-sufficient in terms of meeting domestic hydrogen demand and even acts as a net exporter. To put these figures into perspective of the overall domestic hydrogen uptake: in scenario 1 the consumption of hydrogen for energy purposes was estimated at 233 PJ, of which 70% or about 160 PJ (see Table 5) is imported; in scenario 2 the domestic demand of hydrogen is 355 PJ, against a total domestic production of 375 PJ (i.e. 20 PJ exports); and in scenario 3 domestic consumption is estimated at 463 PJ, of which 43% (or about 200 PJ) is imported. Note that these figures only relate to the hydrogen consumed for energy purposes, and not contain the additional hydrogen that will be needed as a feedstock for the industry, which is estimated to be in the order of 30 to 45% of total hydrogen demand, or between 100 and 200 PJ per year. What is also not included in these figures is the function that the Netherlands may play as a hydrogen trading and transfer hub for North-western Europe insofar as hydrogen imported from the international market is re-exported to surrounding countries (e.g. hydrogen imported in the Port of Rotterdam and transported further to Germany, France, etc.). If the Netherlands succeeds in developing a strong hydrogen hub position in the future, transit flows towards surrounding markets may easily comprise several hundreds of PJ per annum.

Table 5. Net import in PJ

	2015	2050 Scenario 1	 Scenario 2	 Scenario 3
Coal	470	0	0	0
Oil	2,760	2,570	2,570	2,570
Oil products	-1,550	-1,770	-1,770	-1,770
Natural gas	-1,050	130	150	230
Biomass	-50	450	280	270
Electricity	30	50	-30	50
Hydrogen	0	160	-20	200
Total	**670**	**1,630**	**1,210**	**1,560**
Total excluding oil	**-540**	**830**	**410**	**760**

Discussion

Towards the hydrogen economy

A fundamental discussion in the area of energy economics is to what extent electrification of society would be feasible during the time span between now and 2050. As Figure 1 below indicates, the share of electricity in 2015 in the Netherlands amounted to some 20% only (the sum of 17.3% fossil electricity and 2.3% renewable electricity). Most experts seem to agree – given that in the Western world electrification proceeded by some 2 percentage points per decade during the last 40 years (Rats, et al., 2017) – that an increasing share of electricity in the energy mix of about 5 percentage points per decade is the maximum speed of electrification of society (see also the EU Reference Scenario (EC, 2016)). This would mean that electrification could proceed at most from the about 20% level in 2015 towards some 40% by 2050. The scenarios all satisfy this criterion, as has been shown in Figure 1, with the 2050 share of electricity ranging between 35 and 38%. Obviously, the role of renewable power will have increased substantially by that time: in the scenarios, it varied between some 82 (scenario 1) and 95% (scenario 2) of total power production.

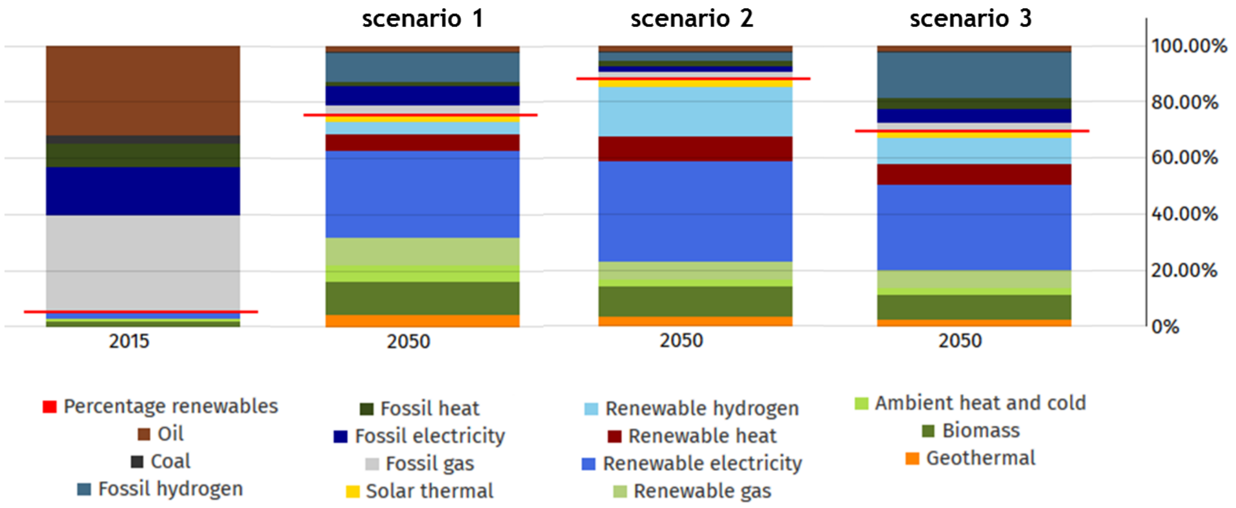

Figure 1. The mix of energy carriers, and the share of renewables

Hydrogen in domestic energetic uptake – i.e. excluding hydrogen exports and disregarding hydrogen as a feedstock – clearly plays a significant role in the various scenarios, although much less in scenario 1 (233 PJ in total) than in scenarios 2 (355 PJ) and 3 (463 PJ). About 60% of the hydrogen is, according to our scenarios, taken up by the industry, especially if fertiliser production is included. The remainder of the uptake is divided among mobility, agriculture, and the built environment in comparable volumes (between 50 and 70 PJ per sector in scenario 3).

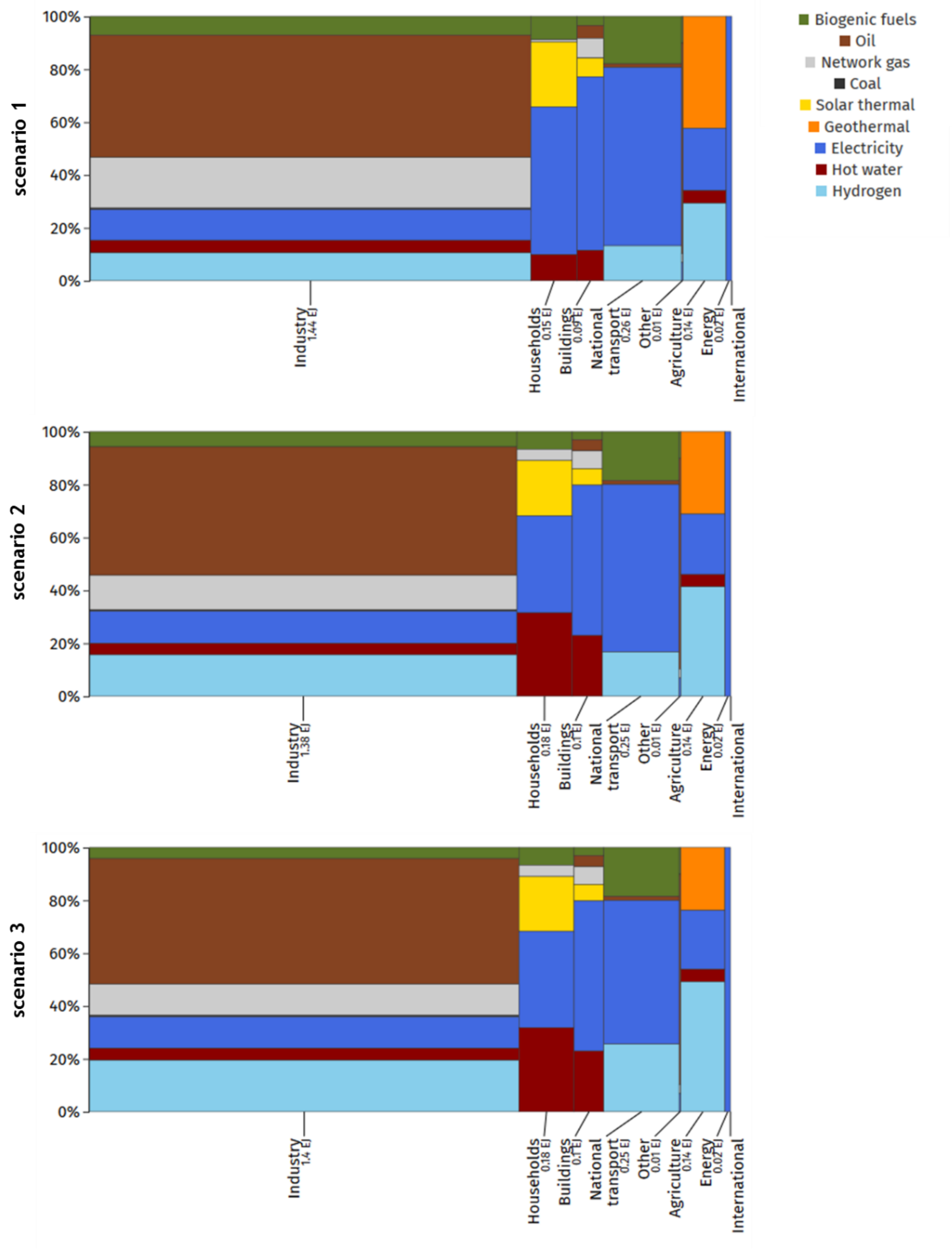

Figure 2. Composition of energy carriers of final energy demand per sector in 2050

The feasibility of any scenario leading up towards a substantial increase of the role of hydrogen in the energy system of the Netherlands depends on a number of assumptions, such as: the legal framework that needs to be in place, the availability of transport and storage capacities that can handle the hydrogen flows, the appliances for hydrogen being available, and obviously the incentives being right for the market to turn towards the uptake of hydrogen. For the latter, policies and measures may be important to get through the so-called 'valley of death'.

On the longer term, obviously, market prices will be crucial. In other words, the market price of blue and green hydrogen will need to be such that private players will turn towards their use. Currently, blue and especially green hydrogen are still positioned in the 'valley of death': volumes produced and consumed are still so small that economies of scale do not yet apply, the legal framework still needs further elaboration, and appliances are not always available on the market against competitive prices. All these challenges will need to be addressed in order to get to the hydrogen energy system of the future.

All this explains why the current, relatively substantial, volumes of hydrogen produced in the Netherlands, some 10 bcm or 0.91 Mt per year (assuming 1 Mt = 11 bcm), is still predominantly 'grey', that is to say, produced from natural gas while releasing the CO_2 from the conversion process into the air. The production costs of this 'grey' hydrogen per kg are currently in the order of € 1.25 to 1.75 for bulk applications according to the scattered information on bulk hydrogen prices. In order to compete, the blue and green hydrogen therefore will need to be produced against comparable prices, assuming that the voluntary green bonus in hydrogen market uptake will remain limited to levels in the order of 10% of the price maximum, and assuming that governments will not actively introduce policies and measures to eliminate the use of 'grey' hydrogen altogether. Whether a long-term cost price of blue and green hydrogen, that is about similar to the comparable cost price of 'grey' hydrogen will be feasible, and when, is still under discussion.[5] A recent study by World Energy Council Netherlands (2018, p. 4) argues, for instance "that electrolysis could become economically viable around 2030. Although this is based on the seemingly ambitious assumption of a trajectory of continued cost reductions mainly for renewable electricity production and electrolysis technology, such cost reductions are comparable to those that have been observed in offshore wind or solar PV." Moreover, there is evidence (WEC and Frontier Economics, 2018) that internationally at many places local costs of power production, notably in regions with high solar irradiance and favourable wind conditions, will be soon such that rather low prices of producing green hydrogen for the international market seem to be feasible if production at sufficient scale would take place.

Some generic socio-economic considerations on the model results

To put the modelling outcomes in the right perspective, a number of observations on the economy of the Netherlands and its energy system in particular can be relevant.

It is clear that the energy transition will have pervasive implications for the overall economic system, given that in the past the Netherlands has relied heavily on the gas from the Groningen field, has increasingly turned into a producer of electricity to the extent of creating a net export position of power, and has developed in the course of time not only into a strong natural gas hub, but also as a distribution hub of energy for North-western Europe, notably via the important role of our sea ports. Also the Netherlands developed a relatively energy-intensive agricultural production system and a relatively strong position in the energy-intensive chemical industry, steel

---

[5] We acknowledge that the price for blue hydrogen will largely be based on and/or linked to the price of fossil fuels. As a result we consider that blue hydrogen will be traded at a premium price relative to grey hydrogen (i.e. this depends on the costs of emitting one unit of CO_2 into the atmosphere relative to mitigating or storing it). The fact that green hydrogen is derived from renewable energy sources will allow green hydrogen to develop its own cost/price trajectory, more independent from fossil fuels.

industry, and refineries. This explains why the energy transition that, on the whole, raises the cost of energy (see also our scenario outcomes) may affect the overall competitiveness of the industry of the Netherlands relatively strongly.

For that reason, and acknowledging that the need for greening the energy system by 2050 is a given, it is important for our economic system to consider how the energy transition is implemented. Losing substantial parts of our industry and the distribution function of our sea ports and energy infrastructure system could substantially reduce the economic position of the Netherlands on the longer term. The current strong role of natural gas and distribution function of oil and related products therefore needs to be replaced by green alternatives in a convincing way, i.e. with a clear national strategy and policies and measures. The three scenarios distinguished in this report therefore, see Table 6 for an overview, have to be seen also in this perspective: will the greening take place in time, and will the process be such that the key strong points of our economic system can be maintained?

Table 6. Overview of the scenario outcomes

	2015	**2050** **Scenario 1**	**Scenario 2**	**Scenario 3**
Overall energy system costs (EUR bn)	31.39	67.89	90.89	72.31
Employment (FTE)	58.700	200.900	323.600	299.200
Energetic CO_2-emissions (Mt)	169.1	33.7	10.8	30.7
Net import (PJ)	-540	830	410	760

So, in order to assess the three scenarios obviously the model outcomes can serve as a valuable illustration, but the results have to be put in the broader perspective of the economy of the Netherlands.

In scenario 1, there is no clear choice, nor for a strong emphasis on renewable production and application, nor for an innovative concept towards a hydrogen economy. The risk of such a scenario is that, although mitigation targets are achieved, our country will not develop a frontrunner stage either with respect to renewables or towards hydrogen in particular. Also the current hub functions towards natural gas and overall energy distribution may get lost. Although employment may increase in the energy system as such, the wider economic implications of this scenario may be disappointing due to the overall loss of innovation and distribution function. Companies traditionally located in our country may tend to move to regions around us.

In scenario 2, the strong focus is on greening the energy system and trying to get substantially less dependent on energy imports. This may put our country in a frontrunner position as far as the introduction of (green) hydrogen and related technology is concerned; it may also put a relatively strong focus on small-scale and decentralised energy systems. Because small-scale decentralised systems on average are relatively labour-intensive as compared to the traditional fossil energy system, and because self-reliance may imply that less advantage is derived from cheap energy imports, the overall costs of this strategy are the highest, but also the positive employment impact. A possible side-effect of this more costly self-reliance strategy is that domestic hydrogen prices and associated energy infrastructure costs can become less competitive internationally. This could negatively affect the competitiveness of hydrogen and energy intensive industries. Another risk may be that our distribution function for energy is slowing down and that part of our energy infrastructure, such as the 120,000 km gas pipeline network, will no longer be used, and need to be replaced by an extended electricity grid. This does not only come at considerable economic costs,[6] but will also have substantial spatial implications. In this scenario, the North Sea offshore wind development will be strong, but the energy is primarily used for domestic consumption.

In scenario 3, our country chooses for a strong focus on hydrogen uptake in the various sectors, not only in the industry and fertiliser production, but also in the built environment, mobility, and agriculture. Because it is recognised that on the longer term hydrogen can be produced in other regions against lower costs, probably with the exception of hydrogen from offshore North Sea wind power combined with using existing gas infrastructure, our country tries to develop into a European hydrogen hub importing from the world market to use either domestically or re-export to the rest of North-western Europe. Also hydrogen as a feedstock will become important in order to establish a green industry, and a green chemical industry in particular. In this scenario, it is expected that the application of hydrogen in all sectors will strongly drive innovation and the potential of exports of hydrogen-related technology and knowledge. That is why the employment multiplier is assumed to be equally high as in scenario 2. The mitigation impact will be slightly less, although still within the 80-95% EU target range, but the overall costs are considerably lower because the energy system is more efficient.

In comparing scenario 2 and 3, it is clear that the employment in the energy sector is largest in scenario 2 (some 25,000 jobs more), but against some € 18 billion higher annual costs. These figures have to be valued and weighted relative to the qualitative aspects mentioned above, i.e. that our country may lose part of its industry and its energy hub function (i.e. alternative or avoided costs).

The scenarios in the perspective of other studies

How do the scenario results described above compare to other analyses of the potential future hydrogen uptake in the Netherlands? Recently, CE Delft (Hers, et al., 2018) conducted a study comparing four recent projections with respect to the hydrogen uptake in Dutch economic sectors by 2050: the so-called 'roadmap hydrogen' (Gigler & Weeda, 2018); the exploration of climate targets by PBL (Ros & Daniëls, 2017); an analysis of the future energy infrastructure (Afman & Rooijers, 2017); and an analysis of the green hydrogen economy in the Northern Netherlands (NIB, 2017). The figure below summarises the main conclusions, and illustrates that on the whole, the four studies concluded that the domestic use of carbon-neutral (blue and green) hydrogen by 2050 will be in the order of 10,000 kton/year. Excluding non-energetic use of hydrogen as feedstock (which is estimated to comprise some 44% of total hydrogen uptake), this figure amounts to about 5,600 kton/year, or about 680 PJ/year.[7] Compared to the results of our modelling, which projects a domestic hydrogen uptake for energy applications by 2050 of between 233 and 463 PJ, one may conclude that our estimates are fairly cautious. A reason for our relatively low figure is that the model considers for economic reasons very low[8] to zero annual load factors for hydrogen-to-power

---

[6] On the whole, transport of electricity is some 10 times more expensive than of gas through a pipeline system (Saadi, et al., 2018).

[7] Assuming that 1 PJ corresponds with about 8.25 kt.

[8] Such hydrogen-to-power generation is typically considered based on the need to balance the grid.

generation. If one, however, assumes that hydrogen-to-power will be part of our energy future in order to balance the e-grid, hydrogen demand can be some 20-25% higher (i.e. some 300 to 580 PJ), assuming the proportions of hydrogen use in power in 2050 in Figure 3. This additional hydrogen, however, will in our scenarios need to be imported, and therefore creates little additional employment, although the overall costs of the energy system will somewhat increase.

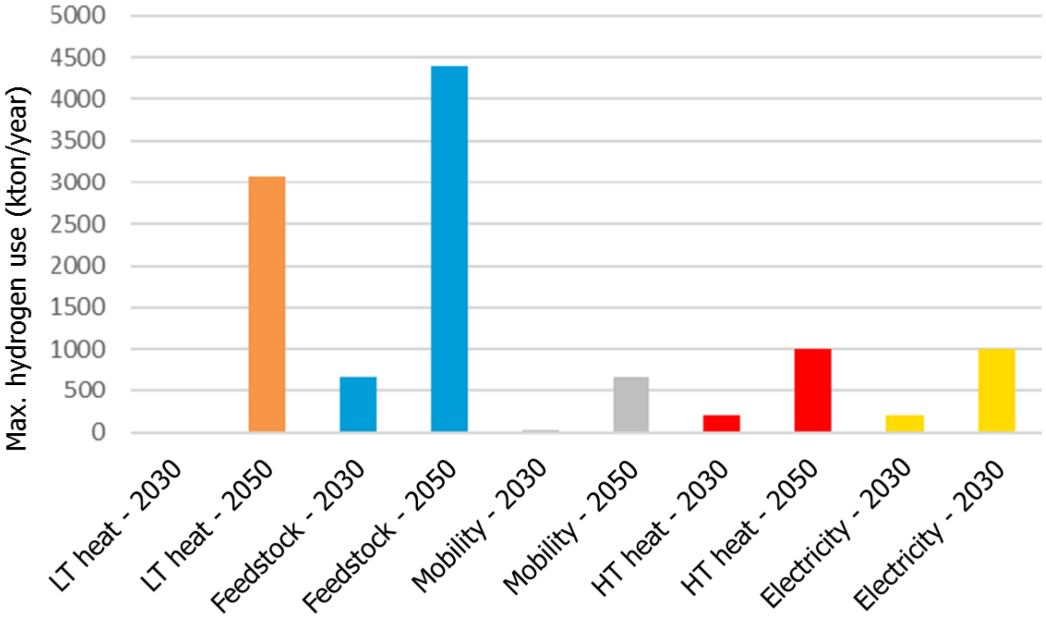

Figure 3. Synthesis of the four studies on the potential for hydrogen in the Netherlands in 2030 and 2050 (Hers, et al., 2018)

Comparing our results with those of the official 'hydrogen roadmap' commissioned by the Ministry of Economic Affairs and Climate (Gigler & Weeda, 2018) leads to the following observations. It has been projected in the roadmap that the overall consumption of hydrogen (both for energetic and feedstock purposes) in the Netherlands could reach a total level of some 14 Mt of which 9.6 Mt energetic hydrogen by 2050, or respectively 1,700 PJ and 1,150 PJ. This is almost double the current level of the hydrogen production of Europe (some 7.8 Mt), but then in the Netherlands alone. Note that this demand projection primarily looks at the technical potential, and in comparison to the several other scenario projections can be considered optimistic towards hydrogen developments. Compared to our scenario 3, where hydrogen consumption was estimated at some 463 PJ, or some 740 PJ if feedstock is included, the figure in the hydrogen roadmap is much larger. This is partly due to the significantly larger role of hydrogen in mobility and the built environment in the roadmap study compared to our more cautious projections.

A recent bachelor thesis by Van Eig (2018) provided an overview of the expectations on the uptake of hydrogen in different economic sectors by 2050 based on interviews with experts. The results of these six expert expectations have been summarised in Figure 4. On the whole, and recognising the wide variety of expert perspectives, the experts seem to be more optimistic with respect to the future role of hydrogen, especially in industry, compared to our projections (see Figure 2).

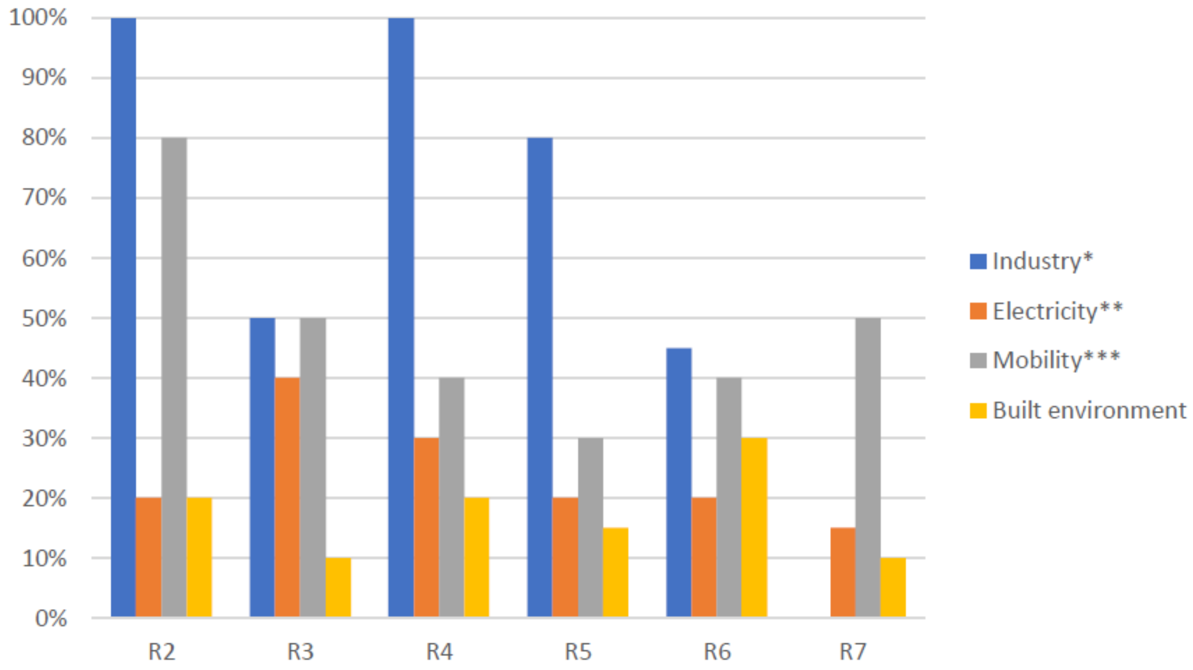

Figure 4. Expert views on the 2050 hydrogen share in energy use per sector (Van Eig, 2018)

A recent study launched by Gasunie and TenneT (2019) that employed the same model as has been used in this study, projected the final hydrogen demand in the Netherlands by 2050 to range between some 360 PJ in the so-called 'local' scenario and some 570 PJ in the 'national' scenario. These figures are somewhat higher than our 2050 projections, ranging between 233 and 463 PJ. This underlines once again the relatively conservative character of our estimates. The Gasunie-TenneT study does not clearly indicate how much hydrogen in addition will be used as a feedstock for the industry (our assumption is that hydrogen as a feedstock uptake represents anywhere between 30 and 45% of total hydrogen uptake by 2050, corresponding with about 140 to 280 PJ of hydrogen if the average share, 37.5%, is used).

A recent projection by the Fuel Cells and Hydrogen 2 Joint Undertaking (2019, p. 9)[9] of the EU-wide employment that may emerge from the upcoming hydrogen industry suggests figures ranging from some 1 million by 2030 to some 5.4 million jobs by 2050. These figures refer to the so-called 'ambitious scenario for hydrogen deployment in the EU'. It is difficult to compare these figures with our results, but if one would use the heroic assumptions that the employment in the Netherlands is some 3.6% of overall EU employment and that the number of jobs lost due to the decreasing fossil energy system is about half the number of the newly-created jobs in the hydrogen industry, then the additional employment for the Netherlands due to the introduction of hydrogen would range in the order of 97,000 jobs by 2050. This figure is comparable to the employment different between our scenario 1 (limited hydrogen production and use) and scenario 3 (embarking on a hydrogen economy).

---

[9] Note that in this report, the 2050 demand for hydrogen represents some 24% of the overall energy consumption (*including* feedstock), whereas in our study (scenario 3) the comparable figure is about 19% (*excluding* feedstock). The figures therefore seem relatively comparable.

Conclusions

To try to make socio-economic projections in a specific sector for 2050 is by definition extremely difficult. Given the timeframe, all kinds of developments in society, in technology, and in policies and measures may take place, both domestically and internationally. Especially for a relatively small, highly internationally oriented, open economy such as the Netherlands, with a relatively strong energy-intensive industrial base as well as a highly-developed international hub function via sea ports and related infrastructures, such developments may have a key impact on the overall economic strength. What matters is that the country responds in a flexible, intelligent, and determined way to a changing environment.

The energy transition clearly belongs to the most pervasive of such changes during the period until 2050. This is true not only: because the traditional strong production and exports of natural gas will come to a halt; but also because there will be a need to set up a strong renewable energy capacity, probably dominated by offshore wind; because of the energy-intensive nature of some of the key economic sectors (agriculture, industry); and because of the strong energy infrastructure for gases, liquids and power.

In this report, the ETM model has been used to project three 2050 scenarios, under the precondition that the 80-95% EU mitigation target for 2050 will be reached, and that the electrification (currently about 20%) will not proceed further than about 40% (in accordance with the EU Reference Scenario). In the first scenario, the Netherlands does not take an active strategic position in the energy transition, but satisfies the international targets. In the second scenario, the Netherlands opts for setting a green example and achieves a near 95% mitigation target by trying to 'get green' quickly in consumption but also in terms of production (i.e. to reduce energy import dependence). Small-scale decentralised energy systems are widely introduced. In scenario 3, the Netherlands strongly chooses in favour of a hydrogen economy. It keeps a strong international position by still acting as an energy hub for North-western Europe, and therefore imports substantial volumes of hydrogen next to the hydrogen it derives from the North Sea offshore wind power production. Also, the application of hydrogen will be quite widespread over the various economic sectors, although still most of the hydrogen is used in the industry, including fertiliser production.

The main conclusions from the report are:

- In all scenarios, the employment in the energy sector increases substantially, raising from the current (2015) levels to about 60,000 FTEs towards levels in the order of 200,000 to 325,000 FTEs. Due to the introduction of green energy, all kind of new applications will need to be introduced as well, implying new knowledge, new technologies, new skills, and new information technology opportunities. So, the employment in the energy system will increase significantly in all scenarios, by at least a factor of three, among others because a greener energy system will be more labour-intensive, and the overall energy costs will increase in all scenarios, from the current about 5% of the total national income to at least double that level by 2050.
- The additional jobs related to moving towards a larger role for hydrogen are difficult to determine precisely, but seem to be in the order of at least 50,000 FTEs; in a strong hydrogen development scenario the employment impact may even rise towards some 100,000 FTEs.

- The energy system will anyhow develop towards a much larger role for hydrogen in the energy system, where it will comprise a share by 2050 ranging between 10 and 20% of the energy mix, and if hydrogen for feedstock is included, between some 15 and 25% of energy uptake.
- In all scenarios, the EU 2050 mitigation targets seem to be feasible.
- In all scenarios, the cost of the energy system will increase substantially to levels at least 2 times the current (2015) costs. A green energy system is generally more labour-intensive than the current fossil system, but also more costly.
- The Netherlands, currently a net exporter of energy if oil (imported, converted and mainly re-exported) is excluded, develops into a net importer of energy in all scenarios (natural gas, biomass, electricity, and hydrogen).
- Scenario 1, in which our country takes a somewhat passive role in the energy transition, almost achieves the mitigation target against lower costs relative to the other scenarios, but does not develop a strategic frontrunner position in the energy transition. The innovation trend in energy is therefore weak and opportunities to create new competitive strengths therefore may be lost.
- Scenario 2 puts heavy emphasis on greening the domestic energy system and achieving as much energy self-reliance as possible. The employment impact of this strategy is therefore the highest and the most ambitious mitigation targets are achieved, but against the highest costs for the energy system. The risks of industry losing competitiveness or even leaving and of losing our traditional energy hub function remain present.
- Scenario 3 strategically opts for introducing hydrogen in all energy sectors, but without the need to produce as much as possible domestically (against higher marginal costs than from the most competitive producers abroad), because it is assumed that – apart from hydrogen production from offshore wind power – hydrogen may be produced against lowest costs elsewhere, to be imported into our country for domestic uptake and re-exports. Also, hydrogen will strongly be used as a feedstock for the industry. In this scenario, the Netherlands may maintain its current strong energy hub function for North-western Europe.

References

Afman, M. & Rooijers, F., 2017. *Net voor de Toekomst,* Delft: CE Delft.

CCAT, 2008. *Fuel Cell Economic Development Plan Hydrogen Roadmap,* East Hartford: The Connecticut Center for Advanced Technology, Inc..

CE-Delft, 2014. *Aardgas in transitie: Denktank Vernieuwing Energiemarkt - Bijlage 5,* Delft: CE-Delft.

CE-Delft, 2016. *Een klimaatneutrale warmtevoorziening voor de gebouwde omgeving - update 2016,* Delft: CE Delft.

CLO, 2017. *Aantal motorvoertuigen, 1990-2016.* [Online]
Available at: https://www.clo.nl/indicatoren/nl002621-aantal-motorvoertuigen
[Geopend 12 December 2018].

EC, 2016. *EU Reference Scenario 2016: Energy, transport and GHG emissions Trends to 2050,* Brussels: EC.

ETM, 2018. *Energietransitiemodel.* [Online]
Available at: https://pro.energytransitionmodel.com

Fuel Cells and Hydrogen 2 Joint Undertaking, 2019. *Hydrogen Roadmap Europe,* Luxembourg: Publications Office of the European Union.

Gasunie & TenneT, 2019. *Infrastructure Outlook 2050,* Groningen: N.V. Nederlandse Gasunie.

Gigler, J. & Weeda, M., 2018. *Countouren van een Routekaart Waterstof,* Den Haag: TKI Nieuw Gas.

Goos, M., Konings, J. & Vandeweyer, M., 2018. Local high-tech job multipliers in Europe. *Industrial and Corporate Change,* 27(4), pp. 639-655.

Hers, S. et al., 2018. *Waterstofroutes Nederland: Blauw, groen en import,* Delft: CE Delft.

Hoogma, R., 2017. *Overzicht van Nederlandse waterstofinitiatieven, -plannen en -toepassingen: Input voor een Routekaart Waterstof,* sl: Dwarsverband.

Hydrogen Council, 2017. *Hydrogen: scaling up,* Brussels: Hydrogen Council.

Hydrogen Europe, 2019. *Hydrogen Europe: projects.* [Online]
Available at: https://hydrogeneurope.eu/projects
[Geopend 11 January 2019].

Kerkhoven, J., Wirtz, A. & Kruip, C., 2015. *Beeldenvan een CO2-arme Nederlandse samenleving in 2050,* sl: Quintel.

Kuijers, T. et al., 2018. *Ruimtelijke verkenning Energie en Klimaat,* sl: Posad Spatial Strategies / Generation.Energy.

Leguijt, C. et al., 2018. *Werk door groene waterstof,* Delft: CE Delft.

MinEZK, 2018. *Kamerbrief betreft Uitfaseren van het gebruik van kolen voor elektriciteitsproductie,* Den Haag: Ministerie van Economische Zaken en Klimaat.

NIB, 2017. *The Green Hydrogen Economy in the Northern Netherlands,* Groningen: Noordelijke Innovation Board.

Quintel Intelligence, 2018. *Rli (voor)Beeld 95% CO2-reductie in 2050.* [Online]
Available at: https://pro.energytransitionmodel.com/scenarios/423882

Rats, M. et al., 2017. *From Molecules to Electrons - What Energy Transition Means for Oil & Gas Investors,* sl: Morgan Stanley Research.

Ros, J. & Daniëls, B., 2017. *Verkenning van klimaatdoelen: Van lange termijn beelden naar korte termijn actie,* Den Haag: Planbureau voor de Leefomgeving.

RVO, 2016. *Best Practice Industriele Warmtepompen - Bevindingen van de Gebruikersgroep Hoge Temperatuur Warmtepompen,* sl: RVO.

Saadi, F., Lewis, N. & McFarland, E., 2018. Relative costs of transporting electrical and chemical energy. *Energy & Environmental Science,* Volume 11, pp. 469-475.

SER, 2018. *Energietransitie en werkgelegenheid: Kansen voor een duurzame toekomst,* Den Haag: Sociaal-Economische Raad.

Van Eig, P., 2018. *Visions on the Potential of Hydrogen as an Energy Carrier for the Future Energy System of the Netherlands,* Utrecht: University College Utrecht.

Van Hoorn, P. & Matthijsen, J., 2013. *Ruimte en energie in Nederland: Een korte verkenning,* Den Haag: Planbureau voor de Leefomgeving.

Vijayagopal, R., Islam, E., Kim, N. & Rousseau, A., 2018. *Cost Benefits Analysis of Technology Improvement in Light Duty Fuel Cell Vehicles - 2018 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review,* Lemont: Argonne National Laboratory.

WEC and Frontier Economics, 2018. *International Aspects of a Power-to-X Roadmap,* London: Frontier Economics Ltd..

Werkgroep Waterstof, 2019. *Waterstof in het klimaatakkoord: Rapportage van de cross-sectorale Werkgroep Waterstof aan de Klimaattafels Elektriciteit en Industrie,* sl: Werkgroep Waterstof.

World Energy Council Netherlands, 2018. *Hydrogen - Industry as catalyst,* Tilburg: Stichting Energieraad Nederland.

Annex I: ETM scenario model inputs

Table A. ETM model input data

Demand		RLi -95% scenario	Scenario 1	Scenario 2	Scenario 3
Households					
o Space heating	Share heating network	10.80%	10.80%	50%	50%
o Hot water	Share heating network	15.00%	15.00%	50%	50%
o Heating network	Share H2 boiler	0.00%	10%	50%	70%
	Share of large scale district heating	57.7%	57.7%	25%	15%
Buildings (non-households)					
o Space heating	Share heating network	0.00%	22	50%	50%
o Heating network	Share H2 boiler	0.00%	20%	50%	70%
	Share of large scale district heating	57.7%	56.4%	25%	15%
Transport					
o Efficiency improvement H2 vehicles	H2 vehicles	0.00%	0.73%	1.25%	1.25%
o Technology passenger cars	Share of H2 fuelled passenger cars	0.00%	10%	16%	30%
o Technology buses	Share of H2 fuelled busses	0.00%	25%	35%	50%
o Technology road freight trucks	Share of H2 fuelled road freight trucks	0.00%	15%	22%	30%
Industry (energetic uses of H2 only)					
o Refineries	Growth of refinery sector	144.50%	90	90%	90%
	Share H2 boiler	0.00%	35%	65%	70%
o Chemical fertilizers	Growth of fertilizer sector	144.50%	144.50%	144.50%	144.50%
	H2 production - share of central H2 network	0.00%	20	50%	60%
	Share H2 boiler	0.00%	35%	50%	60%
o Chemicals	Growth of chemicals sector	144.50%	144.50%	144.50%	144.50%
	Share H2 boiler	0.00%	35%	50%	60%
o Food	Growth of food sector	144.50%	144.50%	144.50%	144.50%
	Share H2 boiler	0.00%	35%	50%	60%
o Paper	Growth of paper sector	144.50%	144.50%	144.50%	144.50%
	Share H2 boiler	0.00%	35%	50%	60%
Agriculture					
o Heating	Share H2 boiler	0.00%	35%	50%	60%
Supply					
Electricity					
o Coal fired	Coal-fired CHP (# = 695 MW plants)	11.5#	0	0	0

o Natural gas	Gas turbine (# = 150 MW plants)	43#	43	0#	0#
	Gas motor (# = 400 MW plants)	12#	12	0#	0#
	Gas STEG CCS	0#	0	17#	17#
Renewable electricity					
o Wind	Onshore (# of 3 MW turbines)	2143.00	2143.00	4,000	2143.00
	Annual load hours	1920.00	1920.00	1920.00	1920.00
	Near shore (# of 3 MW turbines)	521.00	521.00	521	521.00
	Annual load hours	2550.00	2550.00	2550.00	2550.00
	Offshore (# of 3 MW turbines)	7689.00	7689.00	15.000	7689.00
	Annual load hours	3500.00	3500.00	3500.00	3500.00
o Hydrogen	Number (1# = 150 MW)	0.0#	0	0#	
o Solar	Number solar pv plants (1# = 20 MW)	33.8#	33,8	100	33,8
	Annual load hours	867.00	867.00	867.00	867.00
Hydrogen supply					
o Hydrogen production	Wind offshore for H2 (in MWs)	0.00	5000	30000	15000
	Solar pv parks for H2 (in MWs)	0.00	0	2000	0
	Steam Methane Reforming - natural gas (in MWs)	0.00	0.00	0.00	
	Steam Methane Reforming - natural gas + CCS (in MWs)	0.00	0	2500	5000
	Biomass gasification (in MWs)	0.00	0.00	0.00	0.00
	H_2 import (in MWs)	0.00	0.00	0.00	0.00
	Annual load hours (offshore wind)	4.000#	4.000#	4.000#	4.000#
Storage					
o Batteries in households	Share of households with battery storage	0.00%	10%	40%	10%
o Batteries in electric vehicles	Availability for storage	0.00%	10%	50.00%	10%
Flexibility					
o Order of flexibility options	1.Storage in home batteries	1	1	1	1
	2.Storage in electric vehicles	2	2	2	2
	3.Storage in water resevoirs	3	5	5	5
	4.Conversion to hydrogen	4	4	4	4
	5.Conversion to heat for households	5	3	3	3
	6.Conversion to heat for industry	6	6	6	6
	7.Conversion to kerosine for aviation	7	7	7	7
	8.Export	8	8	8	8
	9.Lower production	9	9	9	9
Conversion					
o Conversion to hydrogen	Power-to-hydrogen (1# = 10 MW input)	0.0#	3000#	5000#	5000
o Conversion to heat for households	Power-to-heat (% households with PtH boiler)	0.00%	35%	35%	35%
o Conversion to heat for industries	Power to heat - Chemicals industry (#= 50.3 MW input)	0.0#	19#	64#	64#

	Power to heat – Refineries (#= 50.3 MW input)	0.0#	13#	43#	43#
	Power to heat – Food (#= 50.3 MW input)	0.0#	8#	29#	29#
	Power to heat – Paper (#= 50.3 MW input)	0.0#	2#	7#	7#
o Conversion to kerosine for aviation	Power to kerosine – Aviation (#= 10.7 MWe)	0.0#	0.0#	0.0#	0.0#
Demand side management (DSM)					
o DSM heat pumps	Buffersize space heating - heat pump - AIR (in KWh)	0.00	7.00	7.00	7.00
	Buffersize space heating - heat pump - SOIL (in KWh)	0.00	7.00	7.00	7.00
	Buffersize space heating - heat pump - HYBRID (in KWh)	0.00	7.00	7.00	7.00
	Buffersize hot water households - heat pump - AIR (in KWh)	5.00	5.00	5.00	5.00
	Buffersize hot water households - heat pump - SOIL (in KWh)	5.00	5.00	5.00	5.00
	Buffersize hot water households - heat pump - HYBRID (in KWh)	0.00	5.00	5.00	5.00

Below, a brief discussion based on literature review is provided for some of the ETM model parameters for which the authors have introduced changes.

Demand

Households and Buildings

Space heating and the share of H_2; There are different ways in which the uptake of H_2 in space heating in households and buildings can occur. The current version (12-12-2018) of the ETM model only allows us to introduce H_2 boilers in district heating systems. Ideally we would like to be able to model a direct switch from a household level gas boiler to a H_2-boiler, but the ETM model does not include this option (yet). While building a district heating network with a centralised H_2-boiler might seem the more expensive route, there will also be building specific costs related to replacing gas-fired boilers, and upgrading the existing gas grid. Hence we consider the district heating option a suitable proxy in this case.

Currently, there is no consensus about the techno-economical potential of district heating systems for the year 2050 in the Netherlands. A lot depends on the availability of (residual / geothermal) heat sources, the residual heat demand from buildings (after insulations) and a range of other techno-economic factors. (CE-Delft, 2016) performed a simulation study where 'collective heat' options, like geothermal, CHP and residual heat from industries could serve around 83% of all households in the Netherlands by 2050. On the lower end of the spectrum, we could consider that only the category CHP (at 22% of total) would be suitable for absorbing H_2 as both geothermal and residual heat fuelled district heating does not involve a dedicated combustion process. Hence we consider the range of 22-83% to be a valid range for estimating the share of district heating systems in households and buildings by 2050.

To estimate the max-min share of H_2 as a fuel in district heating systems we can use the same data, where H_2 will only be used in CHP systems or also crowds-out the use of residual and geothermal heat. As a result we find the range of 26-100% share of H_2 in district heating systems.

Transport

As indicated in the literature on the ETM model, today hydrogen vehicles are still a rather new technology, so there is a lot of room for improvement. Even in the case of a marginal uptake of hydrogen (scenario 1), it is therefore assumed that the efficiency of hydrogen vehicles will increase. Vijayagopal et al.'s (2018) business-as-usual scenario estimates for 2045 that the hydrogen storage requirement decreases by 24.5% compared to 2015, or an annual efficiency improvement of approximately 0.73%. Based on targets of the FCTO and VTO offices of the US Department of Energy, The high technology scenario shows an efficiency improvement of 45% up to 2045. This corresponds to an annual efficiency improvement of about 1.25%.

The draft route map hydrogen of TKI Nieuw Gas (Gigler & Weeda, 2018) assumes that hydrogen as a fuel is a good alternative for the segment of the car market that is currently dominated by diesel. For passenger cars, approximately 16% of the cars in the Netherlands currently has a diesel engine (CLO, 2017). This is in line with the projections by the Hydrogen Council (2017, p. 18), that foresee a 11% share for hydrogen in small cars, and a 25% share for hydrogen in medium and large cars.

For buses and trucks, hydrogen is already used in pilot programmes in the Netherlands and other European countries. As indicated by Gigler and Weeda (2018, p. 73), the Netherlands can play an important role in the development of public buses and trucks on hydrogen. Several Dutch regions are experimenting with public buses on hydrogen. It remains to be seen what the share of electric versus hydrogen buses will be, but there is a trend towards electric for short distances and city buses, while hydrogen may be used for the longer distances and coaches. The Hydrogen Council (2017, p. 18) foresees a share of 35% for hydrogen buses by 2050. For trucks, the projected share is set at 22%.

Industry

The ETM model recognises different industry sectors for which different energy options can be selected, including steel, aluminium, other metals, refineries, chemical fertilizers, chemicals, ICT, food, paper and other sectors. However, the model does not allow us to simulate H_2 use for all these sectors, as it assumes that for some industries, mainly metals and ICT sectors, an all-electric solution will be more likely by 2050. The sectors where H_2 use can be simulated via the use of a H_2-boiler, are:

1. Refineries
2. Chemical fertilizers
3. Chemicals
4. Food
5. Paper

On top of that an important aspect that determines future energy (and H_2) demand in these sectors is the expected size of the sector. Within the 'RLi -95% scenario' all the five sectors are assumed to grow cumulatively to 144.5% of its current size. This is equivalent to a continued annual growth of a little over 1% in the 2015-50 period. For the purpose of this assessment we will deviate from this baseline default growth value, for the refineries sector. We consider that the default cumulative growth rate for chemical fertilizers, chemicals, the food, and the paper sector are justified given expected global population growth and related growth in food, fertilizer and consumer chemicals consumption.

For refineries we anticipate a stagnating or (regionally) declining market within Northwest Europe, including the Netherlands. If we take a look at the EU reference scenario (EC, 2016) we can see that EU-28 oil consumption is estimated to decline by 16% in 2050 relative to 2015. For the Netherlands the EU reference scenario estimates a 9% reduction. Also considering that road transport will need to be largely carbon free by 2050, and much higher shares of electricity and hydrogen are anticipated in the EU, we consider that EU refineries will experience lower load factors and possible overcapacities. As an offsetting trend could be that such overcapacity will be used to increase supplies to the international transport fuels and petrochemicals markets. Given both trends we do not anticipate significant cumulative growth in this sector, and consider a the refinery sector to experience a modest decline or stagnation in the range of 80-100% relative to the current size of the sector justified.

For refineries and the chemicals sector implementing high shares of H_2 in the main process, for no-energetic purposes is typically more challenging as it would require more fundamental technological shifts. At the same time implementing higher shares of H_2 for energetic purposes (high temperature heat processes) with the help of H_2 boilers is relatively straightforward. We therefore anticipate that before higher shares of H_2 will be used for non-energetic purposes that significant high shares of H_2 uptake in these industries are feasible by 2050. Industrial sites generally have an economy of scale advantage for developing dedicated H_2 transport grids. For refineries, chemicals and chemical fertilizers we consider that H_2 use for energetic purposes by 2050 can reach very high shares 60-100%, whereas in the food and paper sector lower levels of H_2 use are foreseen (40-80%), mainly due to the biomass use potential for energy purposes in these industries. Also, the food and paper sector are often located more inland (e.g. less close to large supplies of renewable electricity for green H_2 production), and are have a lower level economy of scale level for developing dedicated H_2 infrastructure.

Agriculture

The application of H_2 boilers in agriculture for heating by 2050, is likely to compete with biomass or manure derived bio-energy (e.g biogas from manure digestion). Also, it will be more challenging to ensure that the existing gas grid is completely retrofitted to be able to absorb high levels of H_2. Most farm-houses are typically located in rural areas often at the periphery of gas distribution networks. This makes it less likely that high shares of H_2 can be achieved. However, we anticipate that when local biogas grids or heat networks are being established also in rural areas, these grids and auxiliary systems and appliances will also be developed ‘H_2-ready’. Hence we consider the uptake range for H_2 boilers in agriculture for heating purposes, similar to that in households and buildings (i.e. 26-100%).

Supply

Electricity

Electricity mix

In all scenarios, we assume a full phase-out of coal for electricity production by 2050. The Dutch Minister of Economic Affairs and Climate has proposed a legal ban on the use of coal for electricity production per 2030 (MinEZK, 2018). This is in line with international development related to the phase out of coal.

Based on PBL's exploration of climate targets and the energy sector for 2050 (Ros & Daniëls, 2017), between 1 and 20% of electricity production would still be based on coal and natural gas. In our scenarios, it is assumed coal will be phased out, so this will be fully based on natural gas. The estimated range of 1 to 20% remaining natural gas for power generation is likely to serve as a balancing solution for the electricity system. We consider that by 2050 gas-fired power plants will reduce production first to enable larger quantities of (intermittent) renewable electricity to be fed into the power grid.

The number of wind turbines on land in the Netherlands is currently slightly more than 2,000. Van Hoorn & Matthijsen (2013) have calculated that the maximum potential for 2050, considering also public acceptance, will be between 2,000 and 8,000 wind turbines. A study from 2018 (Kuijers, et al., 2018) discusses various scenarios for wind energy. In the top-down (large scale) scenario, there would be 4,600 wind turbines on land, with a total capacity of 14 GW.

The number of near shore wind turbines is currently slightly above 500. Near shore wind refers to wind turbines within the territorial waters (12 nautical miles or 22.224 km from the coastline). The Dutch government does not plan new wind parks near the coast, but some offshore wind parks may be extended within the territorial waters (between 10 and 12 nautical miles from the coast). A slight increase is therefore possible.

According to Kuijers, et al. (2018), there is space for 36 to 54 GW of wind energy offshore. This would translate to 12,000 to 18,000 wind turbines with a 3 GW capacity. In practice, offshore wind turbines already have a much higher capacity, but the ETM model does not allow for this.

For H_2-fired power generation there are no adequate reference studies and reports to provide us with a range estimate. One could anticipate the share of H_2-power plants to be equivalent to those of natural gas-fired power plants ranging between 1-20% by 2050.

Hydrogen

Hydrogen supply

We anticipate hydrogen supply via two different routes in the ETM model. The first route considers hydrogen supply through utilisation of excess renewable electricity generation, while for the other route there is a dedicated hydrogen production infrastructure for green, grey and/or blue hydrogen. Here we observe that the ETM model applies a higher annual load for offshore wind in the hydrogen supply section, than it does in the electricity supply section (resp. 4.000 vs. 3.500 hours). We consider this distinction relevant, as we expect that future curtailment rates could increase. In case certain offshore wind parks or capacities have a dedicated power-to-hydrogen infrastructure available we assume that curtailment rates will be considerably lower for these offshore wind parks, which would result in a higher total number of annual load hours.

Storage

Electricity

For storage of electricity in household batteries we consider that any house that is connected to a central network or facility for heat supplies does not have significant battery storage capacity available (e.g. 50% of households). Of the remaining 50% of households we only consider all-electric households as most suitable candidates for having a significant battery storage capacity available. We estimate that 35%-point of this will pertain to all-electric houses with significant battery storage capacity. The number of hours per day that an electric vehicle stands idle is considerable.

Given that most passenger vehicles stand idle for well over 80% of their time, for electric vehicles a maximum of about 80% of the batteries' capacity can be used for storage. If we assume that – due to practical challenges of not being able to connect the vehicle to a charging point we consider that around 50% of battery capacity can be used for electricity storage.

Flexibility

Order of electricity flexibility options

There are several options to provide flexibility to the electricity system. Each option has its own total capacity, dispatch and cost rate. Within our scenarios we introduce a slight change in the merit order of the nine flexibility options available in the ETM model. After storage of electricity in batteries (i.e. 'in home' and in electric vehicles) available within the energy system, we consider conversion of power-to-heat for households a more desirable flexibility option relative to 'storage in reservoirs', as the latter type of flexibility will typically be provided by other countries (e.g. Norway). One of the key rationales for this is that we anticipate that due to higher installed on- and offshore wind power capacities, also winter peak production capacities in renewable power can arise. This excess power can be used by households/buildings to store heat in available heat buffer systems.

Conversion

Power-to-heat households

With the announced phase-out of natural gas (low calorific gas) in the built environment in the Netherlands, the market for alternative heat supply options will significantly change in the coming decades. As a result, we assume that also the share of households with a power-to-heat boiler will increase to a maximum of around 35% by 2050.

Power-to-heat industries

(CE-Delft, 2014) estimates that by 2030 around 75 PJ of low temperature heat (i.e. <100 ^{O}C) will be used in industries (i.e. is about 10% of total national low temperature heat demand). However most of the heat consumed in industries is high temperature heat (HT) of >100 ^{O}C. Total HT demand in industries is estimated to be 410 PJ (CE-Delft, 2014) in 2030. Here we assume that the absolute level of heat demand in industries will not materially change.

Knowing that power-to-heat in industries in most cases would involve installing industrial heat pumps, the power-to-heat options cannot serve the total heat demand. However, industrial heat pump innovations suggest that higher temperature ranges can be achieved economically to a maximum of around 250 ^{o}C (RVO, 2016). If we consider that by 2050 also the 100 to 250 ^{o}C temperature range can be covered with heat pumps an additional 80 PJ of heat and thus a total of 155 PJ heat (or 43 TWh) can be supplied with the help of heat pumps. This amounts to a little over 30% of total industrial heat demand. Assuming load hours per heat pump between 5.000-8.000 (6.000 hrs/y) per annum about 300.000 MWh of electricity can be converted into heat for a heat pump with an assumed standard size of 50.3 MWe input capacity. This requires instalment of a total of #143, 50.3 MWe input capacity heat pumps.

- Chemicals ≈ 45% = # 64
- Refineries ≈ 30% = #43
- Food ≈ 20% = #29
- Paper ≈ 5% = #7

Annex II: Modelling constraints, limitations and key assumptions

One of the reasons why our results on the whole can be considered relatively conservative as far as the projected hydrogen 2050 uptake in the Netherlands is concerned, is related to the structure of the Energy Transition Model (ETM). This open source energy systems model is under continuous development; new data inputs and assumptions are often validated by market actors (link). While the current ETM model version allows us to simulate the increased domestic production as well as consumption of hydrogen in different sectors, there are a few features that limit capabilities to introduce hydrogen via different technology options:

- Non-energetic use of hydrogen: The model only covers hydrogen production and consumption for energetic use. Hence non-energetic use of hydrogen (such as *hydrogen as a feedstock* for fertiliser production) are *not included*, while non-energetic uses of hydrogen currently are the dominant application. In other words, if we would include in our scenarios the hydrogen demand for feedstock purposes as well, obviously the hydrogen market potential would be significantly (probably 40-80%; see also 2050 estimates of feedstock shares mentioned earlier) larger.
- Hydrogen uptake in households, buildings and agriculture: For buildings and households the model can only introduce the uptake of hydrogen via introducing heat grids that run on hydrogen. We are therefore *not* (yet) *able to introduce direct hydrogen application* in these sectors via for example converted gas boilers or household hydrogen boilers, which may lead to underestimating the uptake in the built environment. [While this can have an impact on the overall costs of the scenarios (e.g. infrastructure and storage costs for building and expanding heat grids), we consider the modelled cost sufficiently representative. In our scenarios we assume that these modelled costs are sufficiently representative for the alternative costs that would be incurred for a) upgrading the gas grid, b) converting/replacing household/building combustion appliances, and c) increasing hydrogen storage capacities.]
- Cost trajectories and learning curves: For this simulation we did not update projected future cost data for the different energy system technologies. All costs data used in the simulations is documented and referenced within the online version of the ETM model. *Significant cost reductions of specific technologies may therefore be understated* in the absence of inclusion of 'chicken-egg', economies-of-scale and -scope and international competition impacts.
- Hydrogen hub: *The model provides little flexibility and detail to allow for adequate simulation of for instance the merits of a future role for the Netherlands as a hydrogen hub* in North-western Europe, i.e. where hydrogen is channelled through the Netherlands and therefore both imported and exported, thereby creating additional employment and value. First of all the model is tailored to the Netherlands energy system and treats all import and export flows similarly (e.g. in terms of costs, CO_2 footprint, etc.). While working with default or averaged values might seem adequate, it does not do full justice to the real-time dynamics of both todays' and the expected future dynamics of the North-western European energy systems. Secondly, the model has some limitations in simultaneously allowing for increasing domestic production and imports of (renewable) electricity and hydrogen. A final

limiting assumption is that insofar as hydrogen is imported, the model considers this ‛blue’ rather than ‛green’.

- Direct costs and avoided costs: The ETM model does not allow for an assessment of the *economic bonus based on possible avoided societal costs of the hydrogen scenarios*. For instance, in the scenario where the hydrogen economy remains marginal, the conditions for the (petro)chemical industry to continue production in an overall greening economy may be such that this sector altogether will (have to) move to other regions of the world. The costs of such a development in terms of employment and value added could become very substantial for the Netherlands economy. To the extent that the introduction of the hydrogen economy would provide an alternative for these industries to survive in the Netherlands, the positive impact of turning towards hydrogen may well be much larger than reflected in the model results.