Offshore conversion of wind energy to hydrogen on North Sea energy islands

Marcel Weeda en Marit van Hout

Offshore hydrogen production meeting

PtG Expert Group Flanders,

Brussels, 11 January 2017

Background

- TenneT North Sea energy island concept to facilitate:
  - Cost-effective utilization far-shore wind energy potential
  - Optimal energy transmission
  - Further European market integration
- Integration of offshore wind in onshore electricity grid possible and cost effective?
- Can Power-to-Hydrogen conversion be part of the solution?
- Request TenneT (Electricity TSO) to Gasunie (Natural Gas TSO) to join consortium
- Need for upfront order of magnitude analysis:
  - Balance in supply and demand for electricity
  - Potential supply and demand hydrogen; baseload and surplus production
  - Infrastructure cost

The energy islands concept

Scale

A large scale European roll-out for offshore wind delivers a significant contribution to cost reduction.

Location

When far shore becomes necessary, shallow waters with great wind conditions contribute to cost reduction.

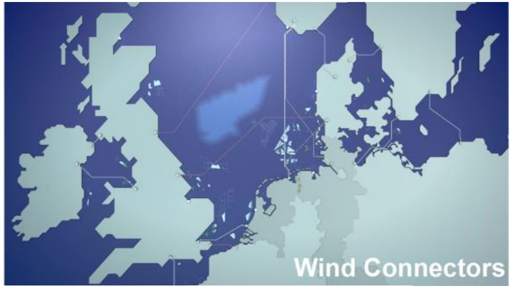
Wind connector

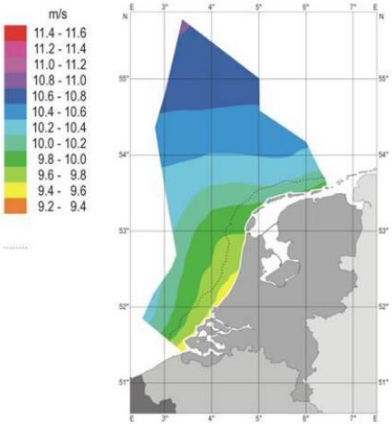
The wind connector combines large scale wind farms with powerful interconnectors for higher system efficiency.

Hub function/ island

By connecting the interconnectors on the island, a hub can be build that facilitates optimal energy transmission and a further European Market integration.

November-16-2016 Future North Sea Infrastructure





Source: Alan Croes, TenneT, KIVI symposium EnergyNL2050, 9 Feb 2017

Indicative figures energy islands

- Possibly three islands: 6 km^2 each, 200 mln m^3 sand
- €1.5 bn (rock and sand only, no infra/facilities)
- Possible connections to existing pipeline infrastructure
- Facilitates approx. 30 GW of wind farms per island
- 15 Converter stations (2 GW each) on the island
- Total: 70 GW, 7,000 turbines (10 MW)
- On the Dogger Bank: 11,400 km^2
- Hard substrate: 4.4 km^2 (0.02% of total Dogger Bank surface)

Source: Alan Croes, TenneT, KIVI symposium EnergyNL2050, 9 Feb 2017

Approach impact assessment large-scale offshore wind

- Excel-based “copper plate model” on hourly basis derived from detailed European electricity market model (COMPETES)
- Geographic scope includes BE, DE, DK, NL, NO and UK
- Use of TYNDP2016 ENTSO-E Vision 4 – Green Revolution scenario for year 2030 for type and amount of installed generation capacity, electricity demand projections and hourly demand profiles, energy prices and CO2-price
- Climate year 2012 for hourly profile wind energy supply and 2015 for solar energy
- Various cases additional offshore wind capacity: 70 GW, 90 GW and 190 GW
- Dedicated wind electricity supply profile for Dogger Bank area
- No limitations in trade capacity: hourly electricity price is equal to marginal production cost of last producing unit in each hour

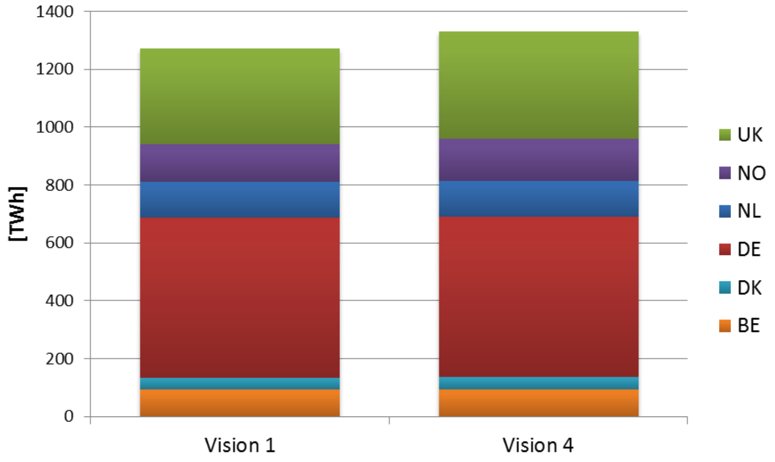
Well-informed picture but with some limitations

- Potential large-scale offshore wind situation for 2050 but electricity demand and demand profile are for 2030
- No further deployment onshore wind and solar-PV toward 2050 included
- No limitations of trade/transmission capacity between North Sea countries
- Interconnection capacity with other EU countries not included
- Effect on investment decisions not taken into account, e.g. for back-up capacity with increasing share of renewables
- Unit commitment characteristics not taken into account (e.g. ramp-up/down rates)
- No use of Pumped Hydro Storage capacity: about 25 GW in North Sea region
- Age structure of production park and differentiation in efficiency
- …

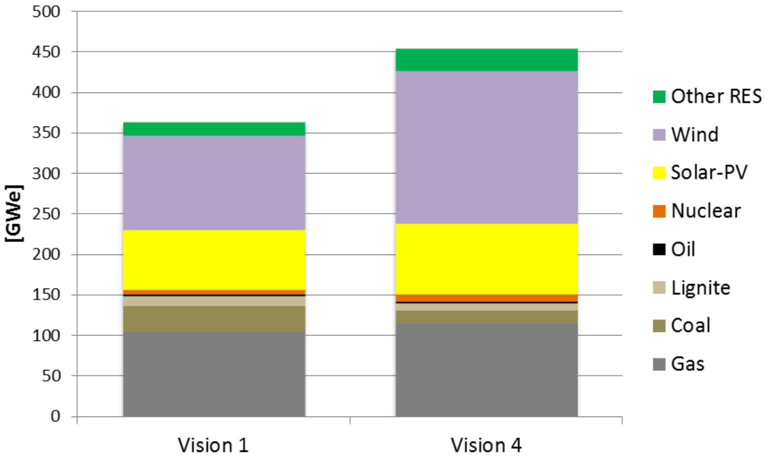
Starting points electricity demand and supply

- Electricity demand and installed generation capacity in the North Sea region according to ENTSO-E Vision 1 and Vision 4 in 2030 (TYNPD2016).

Electricity demand



Installed generation capacity



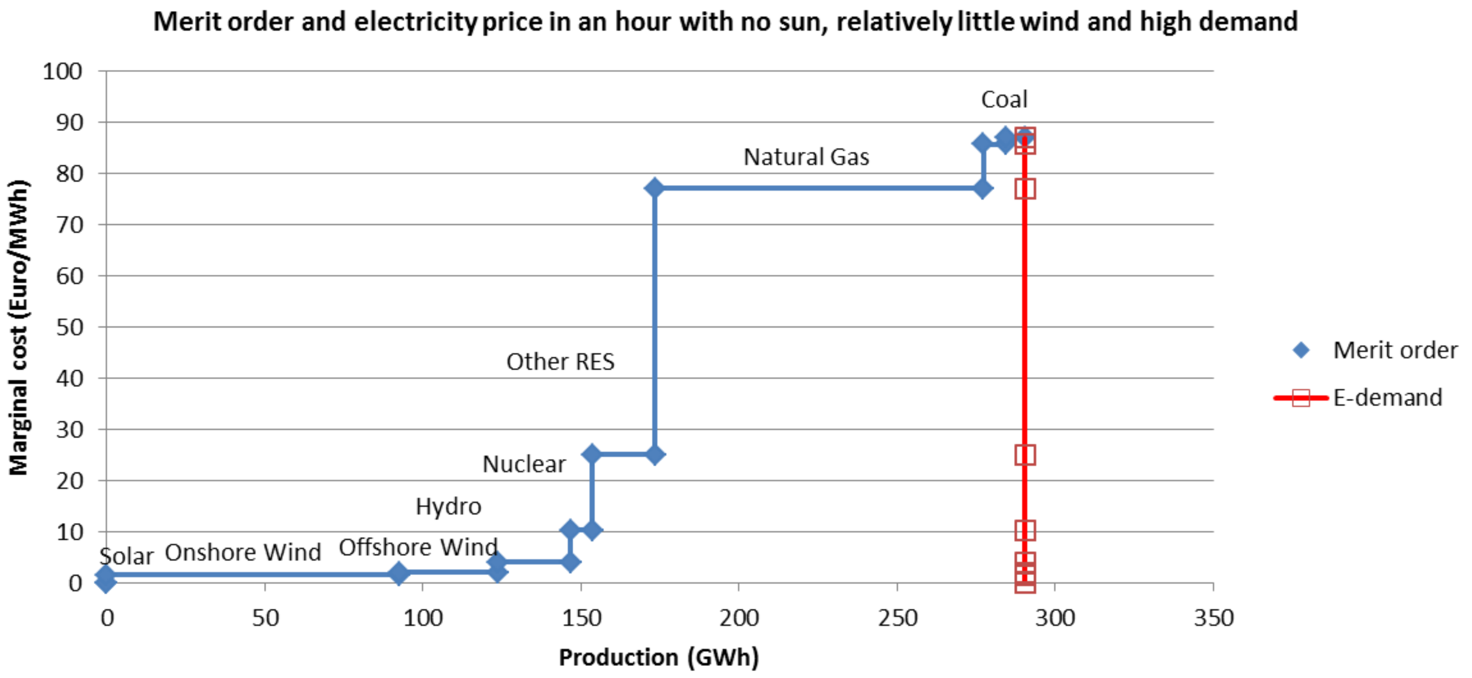
Marginal cost generation options and merit order Vision 1 (b.a.u.) and 4 (Green Revolution)

Technology*	Marginal production cost (€/MWh):		Merit order	
	Visie 1	Visie 4	Visie 1	Visie 4
Solar PV	0	0	1	1
Onshore Wind	1.5	1.5	2	2
Offshore Wind	2	2	3	3
Conventional Hydro power	4.0	4.0	4	4
Nuclear	10.3	10.3	5	5
Lignite	29.2	85.8	6	8
Other RES (stand-alone biomass and waste)	33.5	25.0	7	6
Coal	44.1	87.0	8	9
Natural Gas	69.9	77.1	9	7
Oil	225.7	229.4	10	10

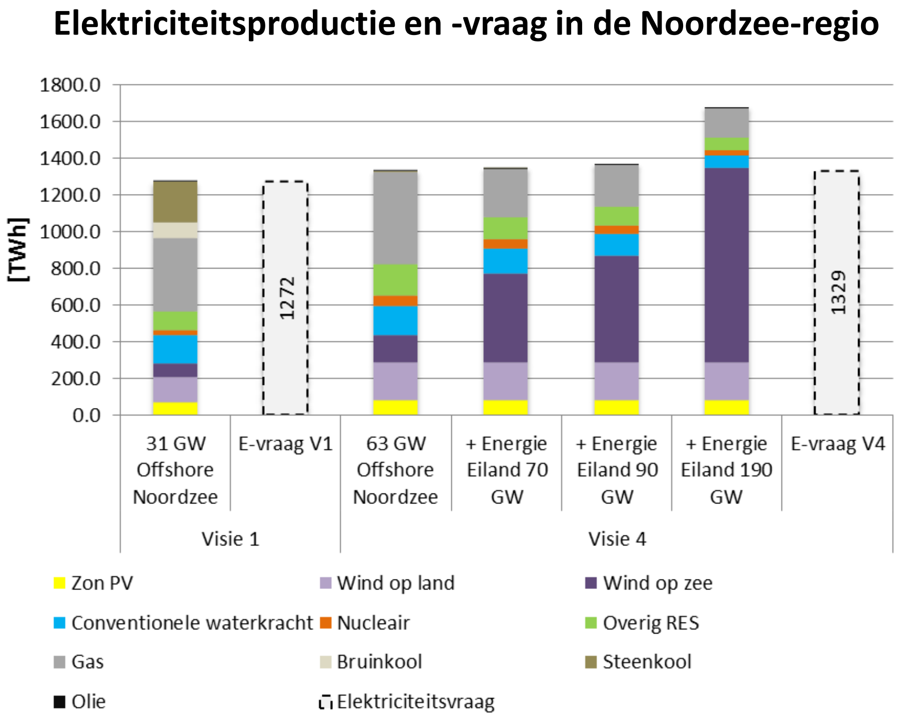
* No application CCS| CO_2 price in (€/ton) in Vision 1: 17 €/ton; in Vision 4: 76 €/ton| Vision 4: use of natural gas before coal.

- Marginal cost = fuel cost + cost of CO_2 + variable maintenance costs

Illustration merit order and determination electricity price for an arbitrary hour (based on Vision 4 data)



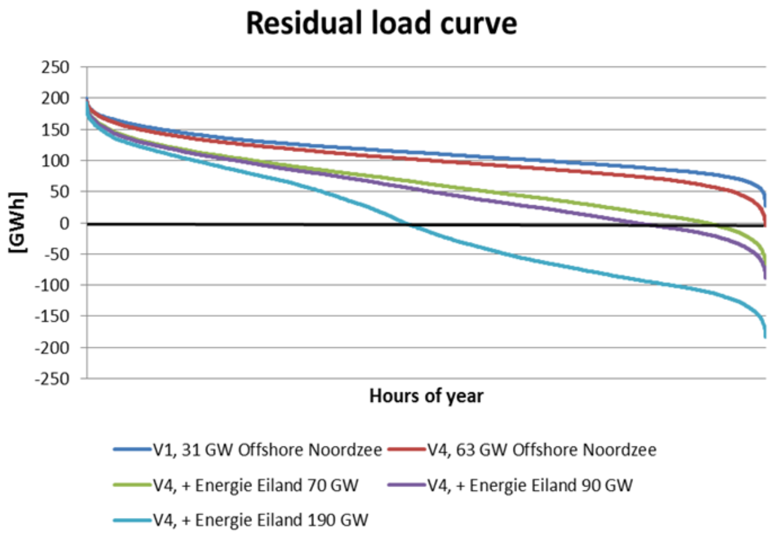
Results annual electricity production

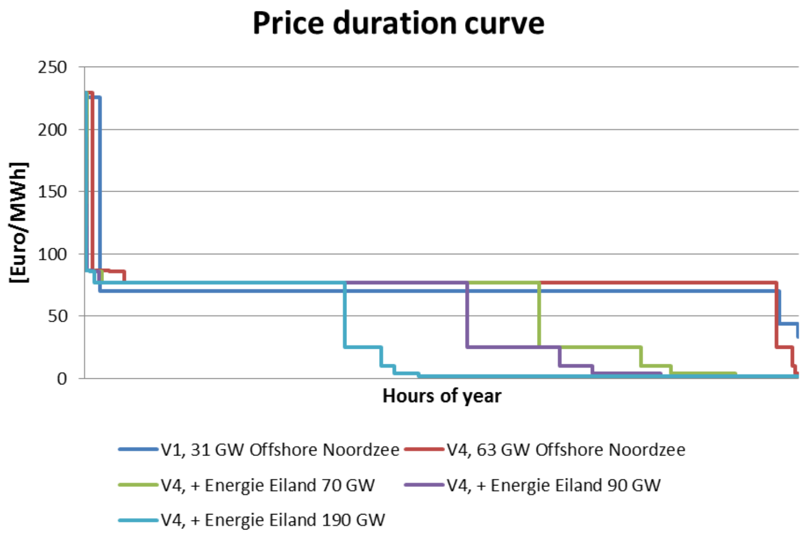


- The use of more expensive technologies decreases with increasing share of wind
- At the same time the chance of an oversupply of electricity from wind increases. If the electricity can not be transported to areas where there is no oversupply, curtailment takes place

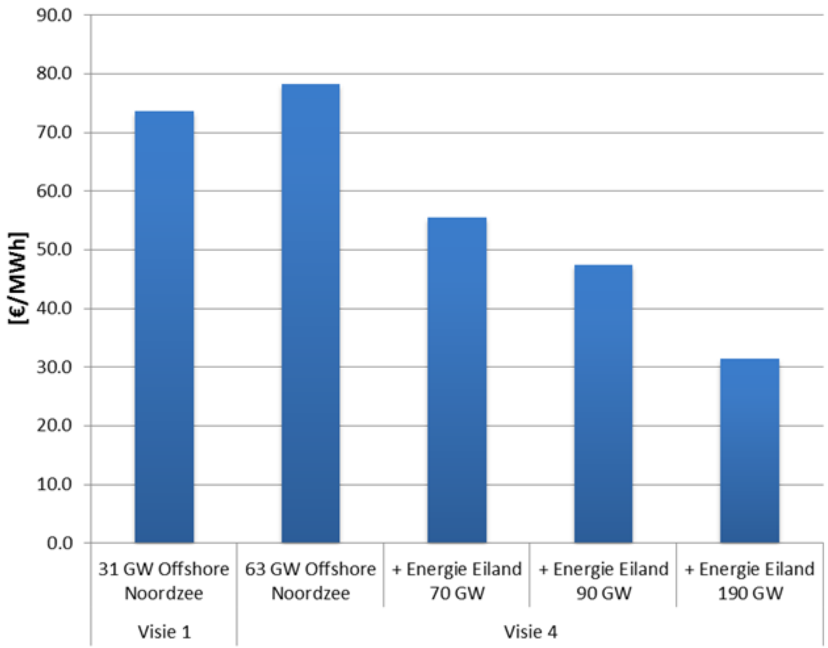
Results residual load duration and price curves

- Residual electricity demand after deduction of solar-PV, and onshore and offshore wind, and electricity prices throughout the year ranked from high to low





Results weighted annual average electricity price



- An increasing share of wind in the mix reduces the electricity price
- N.B.: assumptions for demand and supply without additional 70-190 GW offshore wind illustrate 2030 situation. Potential effects towards 2050:
  - Increase of demand trough electrification resulting in an upward pressure on electricity prices
  - A larger supply of electricity from solar-PV and onshore wind resulting in a downward pressure on electricity prices

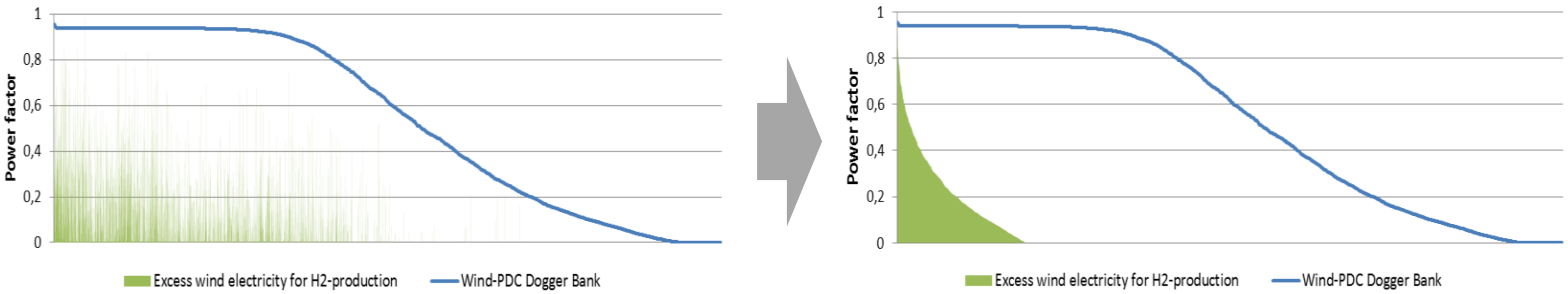
Analysis H_2-production from excess wind electricity

- There is excess when total electricity production from the sun and wind in a certain hour exceeds the demand for electricity; offshore wind curtailed first

Hydrogen production from excess offshore wind electricity, case Vision 4 + 90 GW:

Excess wind correlated to PDC

Excess wind ranked/not correlated to PDC



- Prodution with excess wind requires substantial capacity for limited production, and requires highly flexible robust technology

Results H_2-production from excess wind electricity

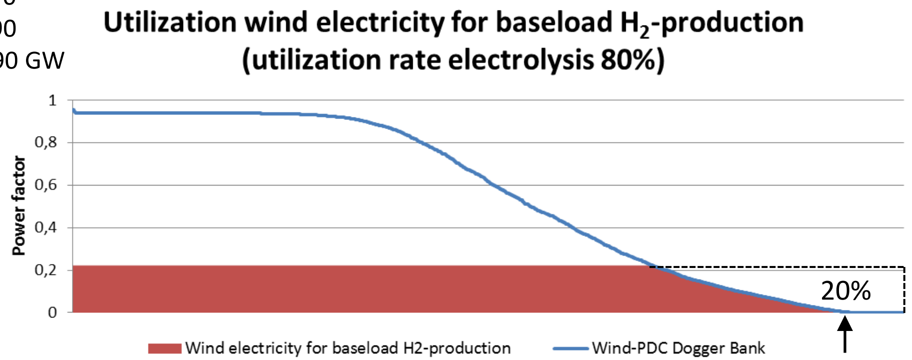
- Electrolysis capacity is equal to maximum curtailment in GWh/h (= GW)
- Electricity consumption 50 kWh per kilo H_2

ENTSO-E scenario:	Wind scenario, with (total offshore wind, in GW)	Maximum hourly excess capacity (GW)	Number of hours excess (hrs)	Full load hours (hrs)	Total surplus (TWh/a)	H_2-production (Mton/a)
Vision 4	+ energy islands, 70 GW (133 GW)	70	767	188	13	0.3
	+ energy islands, 90 GW (153 GW)	89	1 684	396	35	0.7
	+ energy islands, 190 GW (253 GW)	183	4 659	1 890	345	6.9

- Only substantial excess wind electricity at 190 GW
- Total system grows gradually; substantial excess electricity will probably never arise

Analysis H_2-production in base load

x 70
90
190 GW



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ENTSO-E scenario:	Wind scenario, with (total offshore wind, in GW)	Base load operation (defined as 80% utilization rate)				
		Capacity electrolysis (GW)	Operating hours (hrs)	Full load hours (hrs)	Total electricity consumption (TWh/a)	H_2-production (Mton/a)
Vision 4	+ energy islands, 70 GW (133 GW)	15	8 225	7 023	105	2.1
	+ energy islands, 90 GW (153 GW)	20	8 225	6 991	140	2.8
	+ energy islands, 190 GW (253 GW)	41	8 225	7 017	288	5.8

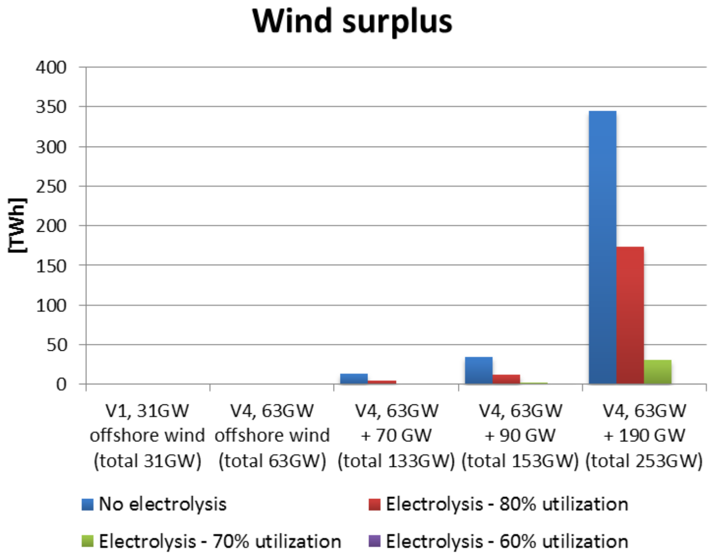
Baseload H_2-production at different utilization rates

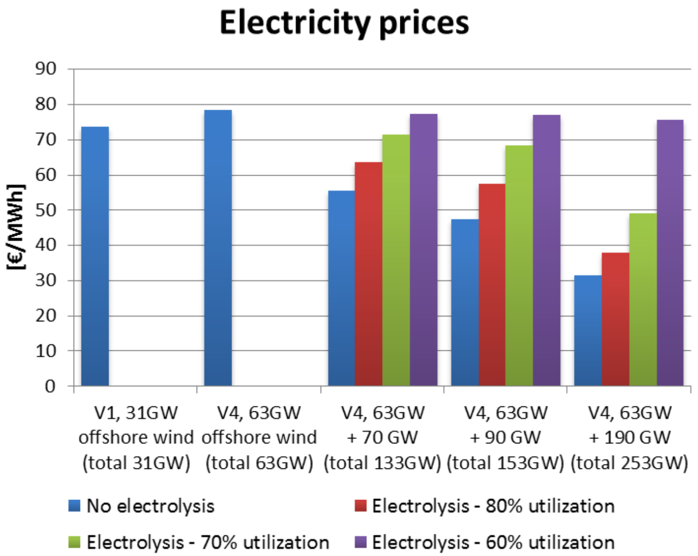
Offshore wind (GW)	Capacity electrolysis (GW)	Utilization rate (%)	Full load hours (hrs)	Hydrogen production (Mton H_2/a)
+30	7	80%	6 948	1.0
	15	70%	6 133	1.8
	26	60%	5 284	2.7
+70	15	80%	7 023	2.1
	35	70%	6 133	4.3
	62	60%	5 241	6.5
+90	20	80%	6 991	2.8
	45	70%	6 133	5.5
	79	60%	5 259	8.3
+190	41	80%	7 017	5.8
	95	70%	6 133	11.7
	167	60%	5 257	17.6

- Total production of 190 GW offshore wind in Dogger Bank area: 911 TWh
- Full conversion to hydrogen requires 182 GW electrolysis. The hydrogen production amounts to 18.2 Mton/a

Impact various cases of base load operation on electricity prices and excess wind

- Extra demand for electricity from base load production results in a reduction of excess wind, but also an increase of conventional generation and thus higher prices





Summary/comparison of hydrogen production in base load and from excess wind electricity

Base load production

ENTSO-E scenario:	Wind scenario, with (total offshore wind, in GW)	Base load operation (defined as 80% utilization rate)				
		Capacity electrolysis (GW)	Operating hours (hrs)	Full load hours (hrs)	Total electricity consumption (TWh/a)	H_2-production (Mton/a)
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Production from excess wind electricity

ENTSO-E scenario:	Wind scenario, with (total offshore wind, in GW)	Maximum hourly excess capacity (GW)	Number of hours excess (hrs)	Full load hours (hrs)	Total surplus (TWh/a)	H_2-production (Mton/a)
Vision 4	+ energy islands, 70 GW (133 GW)	70	767	188 (2%)	13	0.3
	+ energy islands, 90 GW (153 GW)	89	1 684	396 (5%)	35	0.7
	+ energy islands, 190 GW (253 GW)	183	4 659	1 890 (22%)	345	6.9

Indicative potential future H_2-demand: road traffic

- Estimate based on gasoline and diesel sales (Eurostat statistical data).
- NL diesel converted to hydrogen:
  - Diesel vehicles in NL mainly high mileage cars, buses and trucks; rest can be battery electric,
  - Energy share of diesel in NL applied to total of gasoline and diesel in other countries.
- Energy consumption FCEVs 50% of comparable current average diesel car.
- Potential other transport applications not considered, e.g. inland shipping.

Wegverkeer	Eenheid	BE	DE	DK	NL	NO	UK	Totaal
Gasoline 2014	ktoe/a	1.308	18.461	1.322	3.938	933	13.950	39.553
Diesel 2014	ktoe/a	7.156	34.132	2.590	5.951	3.288	25.193	78.310
Estimate required H_2 for FCEVs	Mton/a	0.9	5.5	0.4	1.0	0.4	4.1	12.3
Electricity needed for H_2 production	TWh/a	44	276	21	52	22	204	619

Replacement current industrial H_2 SMR production

- Current industrial hydrogen, excluding by-product hydrogen. Mainly for ammonia production and oil refinery. Furthermore, many smaller applications.
- No estimate of potential future demand for hydrogen sustainable chemical industry based on biomass, circular carbon and CO_2 air capture.
- Also no estimate for replacement of natural gas by hydrogen for high temperature process heat for the industry (next sheet).

Industry (non-energy use)	Unit	BE	DE	DK	NL	NO	UK	Total
Current SMR H_2 production (estimate)	mrd m^3/a	4.0	14.7	0.2	7.6	1,0	4.0	31.5
Current SMR H_2 production (estimate)	Mton/a	0.3	1,3	0,02	0,7	0,1	0,4	2.8
Electricity for H_2 productie	TWh/a	18,8	66.2	0.9	34.2	4.5	18.0	142

Indicative potential future H_2-use for industry high temperature process heat

- Replacement of natural gas by hydrogen as fuel for high temperature process heat in the industry; heat >250°C.
- Natural gas use for process heat in refineries in NL of the same order of magnitude as industry; potentially also in other countries with refineries; not taken into account.
- No estimate for peplacement of natural gas by hydrogen for space heating in existing buildings where electrifcation (heat pumps) or district heating is not feasible.

Industry (process heat >250 °C)	Unit	BE	DE	DK	NL	NO	UK	Totaal
Estimate current natural gas use	PJ/a	41	212	7	50	21	89	420
H_2 needed for replacement	Mton/a	0.3	1.8	0.1	0.4	0.2	0.7	3.5
Electricity for H_2 production	TWh/a	17	89	3	21	9	37	175

Indicative potential future H_2-demand steel industry

- Conversion from current Blast Furnace/Basic Oxygen Furnace to hydrogen based Direct Reduced Iron process with further processing in Electric Arc Furnace. (Electricity use EAF not considered in below figures)
- Assumptions for steel production in the long term:
  - 50% via recycling
  - Rest 100% conversie form BF to H_2-DRI; 570 Nm^3 H_2/ton pig iron

Iron and steel	Unit	BE	DE	DK	NL	NO	UK	Total
Steel production 2014 (Eurostat)	Mton/a	7.3	42.9	0	7.0	0	12.1	69.3
Estimate H_2-demand for DRI	mrd m^3/a	2.1	12.2	0	2.0	0	3.4	19.8
Estimate H_2-demandvoor DRI	Mton/a	0.2	1.1	0	0.2	0	0.3	1.8
Electricity for H_2 production	TWh/a	9.4	55.1	0	9.0	0	15.5	89.0

Indicative potential future H_2-demand as fuel for electricity production in power plants

- Hydrogen for gas fired power plants based on “copper plate model” results. In the future possiby also fuel plant plants (local, decentral, central) with similar efficiency.
- Round-trip efficiency van 37% (67% LHV for electrolysis and 55% for electricity production; optimisation possible to >40%)
- Electricity production with hydrogen produced through electrolysis results in a large increase in electricity demand; potentially requiring extra production with fossil

Power Plants	Unit	BE	DE	DK	NL	NO	UK	Total
Production gas fired power plants	TWh/a	260 (@70 GW);		228 (@90 GW);		162 (@190 GW)		162-260
H_2 needed for electricity production	Mton/a	14 (@70 GW);		12 (@90 GW);		9 (@190 GW)		9- 14
Electricity needed for production H_2	TWh/a	709 (@70 GW);		623 (@90 GW);		442 (@190 GW)		442-709

Overview estimates potential future hydrogen demand

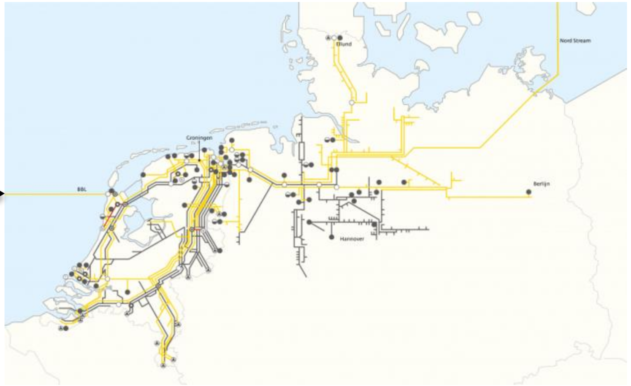
Electricity demand for H_2-production per sector/application in TWh	BE	DE	DK	NL	NO	UK	Total	H_2-production Mton/a
Road traffic	44	276	21	52	22	204	619	12
Current industrial hydrogen	18	66	1	35	5	18	142	3
Fuel HT-heat industry (replacing NG)	17	89	3	21	9	37	175	4
H_2-based DRI process iron & steel	9	55	0	9	0	16	89	2
Gas-based power plants	709 (@70 GW) – 442 (@190 GW)						709-442	14-9
Offshore wind for H_2-production	**330-279 GW @ 60% load factor (5256 full load hours)**						**1734-1467**	**35-30**

- Hydrogen demand potentially much higher resulting from:
  - Future sustainable chemistry based on biomassa and “circular carbon”;
  - Sustainable synthetic fuels (e.g. aviation, international shipping)
  - Residential heating (e.g. old existing buildings, inner cities)
- Offshore wind estimates 330-279 largely additonal to already assumed 133-253 GW

Transport offshore wind energy as H_2 by pipelines

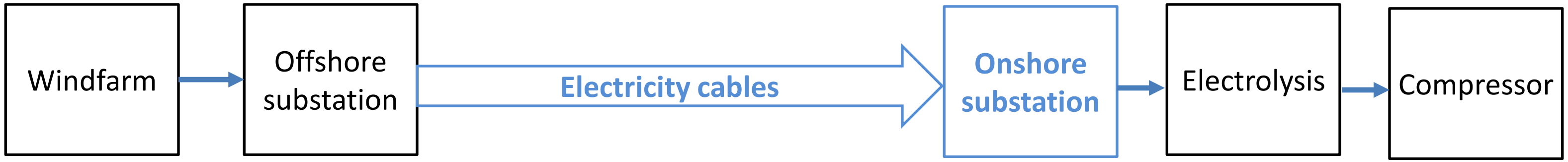
Existing hydrogen transport pipeline system

Existing natural gas pipeline system

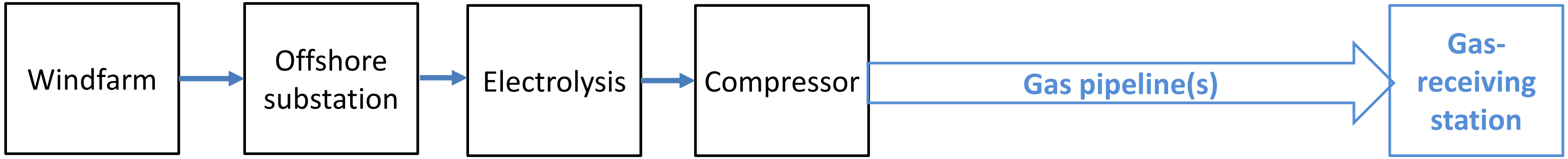


Comparison electricity and hydrogen transport

- Transport as electricity



- Transport as hydrogen



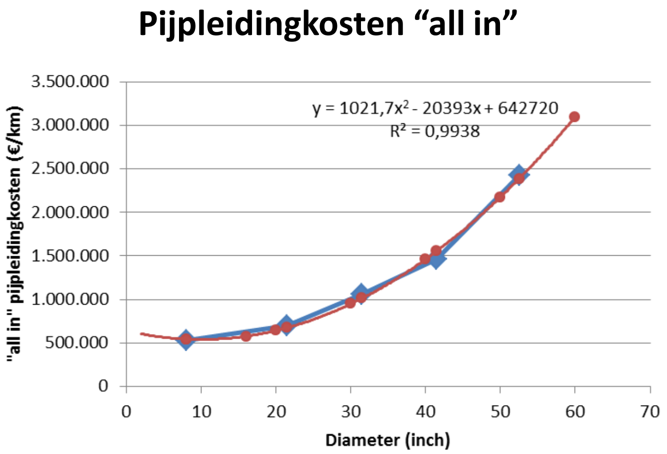
- Many system components are the same: comparison boils down to a comparison of the cost of offshore electricity cables and onshore substation with the cost of offshore pipeline(s) and onshore gas receiving station

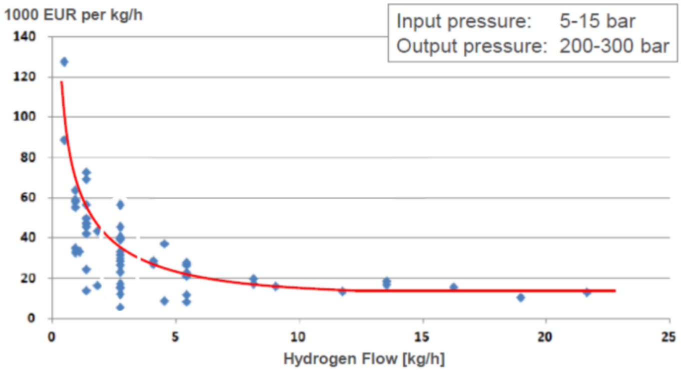
Assumptions cost analysis electricity infrastructure

Cost type	Capacity	Cost	Remark
Electricity cable	750 MW	400 k€/km	Installation of cable pairs with combined capacity of 1200 MW: 800 k€/km
Electricity cable	1250 MW	500 k€/km	Installation of cable pairs with combined capacity of 2000 MW: 1000 k€/km. In the future 2500 – 3000 MW seems feasible
Installation cable pair		525 k€/km	Installation 350 k€/km for a cable. Factor 1.5 for installation of a cable pair
Onshore substation		161 €/kW	These costs have a large spread, among others due to land cost. Value is possibly somewhat conservative
Construction onshore substation		8 €/kW	

Bron: Personal communication,
E.J. Wiggelinkhuizen, ECN Wind Unit

Assumptions cost analysis gas pipeline infrastructure

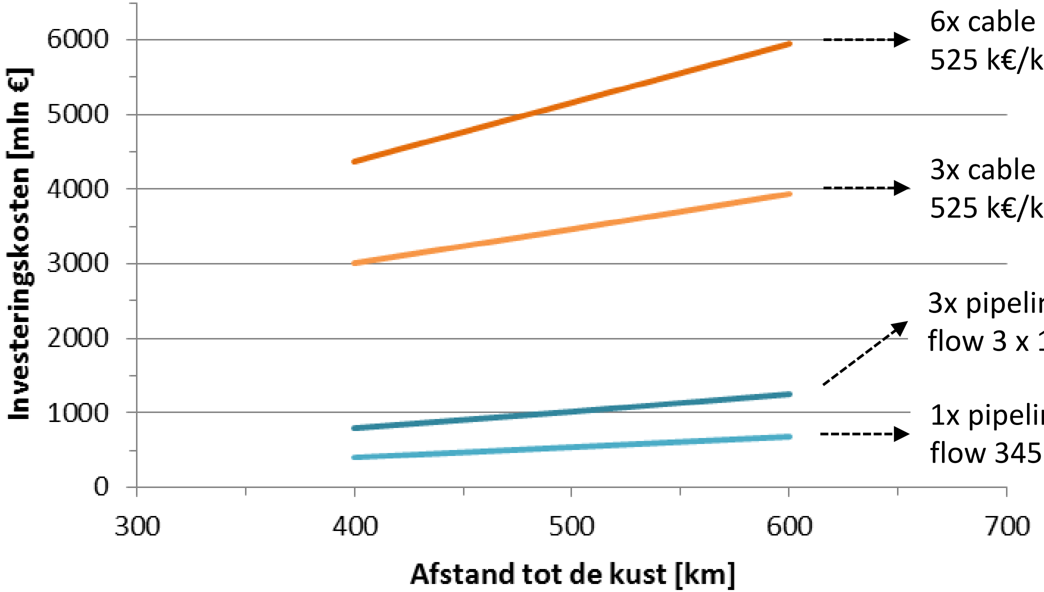




- ACER, 2015: "all in": cost of all activities and materials, such as e.g. engineering, permitting, construction, commissioning, material procurement
  - Analysis of many onshore natural gas pipline projects, but results appear representative for offshore pipeline costs (Source: personal communication EBN)
  - Costs of gas receiving station are low and neglected in the comparison
  - Costs for a compressor are taken into account in the cost estimate of the pipeline infrastructure, but the costs are small compared to the pipeline (Source: Ulleberg, ICE2017)

Results cost comparion offshore electricity and gas infra (1/2)

- Indicative infrastructure costs for transport of energy of 7 GW offshore wind (part of 30 GW energy island) to shore as electricity or as hydrogen:



6x cable pair of 1,2 GW @ 800 k€/km/pair + 525 k€/km install. + 169 €/kW onshore substation

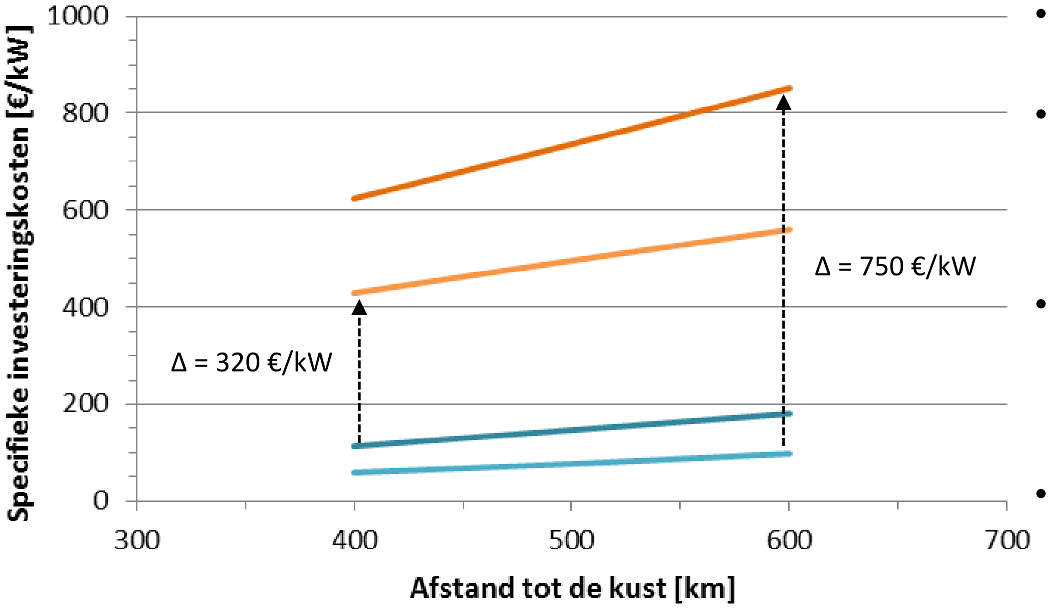
3x cable pair of 2-2,5 GW @ 1000 k€/km/paar + 525 k€/km install. + 169 €/kW onshore substation

3x pipeline ∅ 21-22 inch + compressor; flow 3 x 115 m^3/s; P_{in} = 95 bar en ΔP = 20 bar

1x pipeline ∅ 32-34 inch + compressor; flow 345 m^3/s; P_{in} = 95 bar en ΔP = 20 bar

Results cost comparion offshore electricity and gas infra (2/2)

- Indicative infrastructure costs for transport of energy of 7 GW offshore wind (part of 30 GW energy island) to shore as electricity or as hydrogen:



- Difference in specific investment costs 320 – 750 €/kW_{wind}
- The amount of energy transported by the electricity cable(s) is about factor 1.5 higher than for pipeline due to conversion loss electrolysis.
- Based on indicative cost analysis, offshore conversion seems attractive if there is a demand/-market for “green” hydrogen.
- Indications positive but further integrated energy system, cost of H_2 and business case analysis is needed to assess real potential.

Main insights and conclusions

- The potential amount of excess electricity increases with increasing deployment of offshore wind. The current analysis with total 253 GW offshore wind shows 345 TWh potential excess electricity, which is equivalent to some 6,9 Mton of hydrogen.
- Further electrolytic hydrogen production, using more than the potential excess electricity will require additional fossil-based electricity
- Base load-type production of hydrogen of the same order as with potential excess electricity is possible without affecting the electricity price too much; average prices may increase somewhat, but investment cost for electrolysis are much less.
- The potential demand for “climate neutral” hydrogen in a sustainable enery system seems much larger than the available potential from local RES; this indicates that large-scale import is needed and/or hydrogen from natural gas combined with CCS.
- Based on the indicative infrastructure cost analysis, offshore conversion of wind energy to hydrogen seems attractive if there is a demand/market for “green” hydrogen.

M. Weeda and M. van Hout, Verkenning Energiefunctionaliteit Energie Eilanden Noordzee, report number ECN--17-064, 2017
http://www.ecn.nl/docs/library/report/2017/e17064.pdf

Thank you for your attention

Vragen?:

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